



US006537315B2

(12) **United States Patent**  
**Yamazaki et al.**

(10) **Patent No.:** **US 6,537,315 B2**  
(45) **Date of Patent:** **\*Mar. 25, 2003**

(54) **AUXILIARY ARTIFICIAL HEART OF AN EMBEDDED TYPE**

Jun. 23, 1992 (JP) ..... 4-188813  
Feb. 19, 1993 (JP) ..... 5-030617

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(51) **Int. Cl.<sup>7</sup>** ..... **A61M 1/10**  
(52) **U.S. Cl.** ..... **623/3.13; 600/16; 415/900**  
(58) **Field of Search** ..... 623/3.13, 3.1, 623/3.15, 3.24, 3.26; 600/16; 415/900

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(\* ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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This patent is subject to a terminal disclaimer.

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(21) Appl. No.: **09/878,276**

(22) Filed: **Jun. 12, 2001**

(65) **Prior Publication Data**

US 2001/0041934 A1 Nov. 15, 2001

**Related U.S. Application Data**

(60) Division of application No. 09/469,290, filed on Dec. 22, 1999, now Pat. No. 6,302,910, which is a division of application No. 08/603,193, filed on Feb. 20, 1996, now abandoned, which is a continuation-in-part of application No. 08/505,784, filed on Jul. 21, 1995, now abandoned, which is a continuation-in-part of application No. 08/079,817, filed on Jun. 22, 1993, now abandoned.

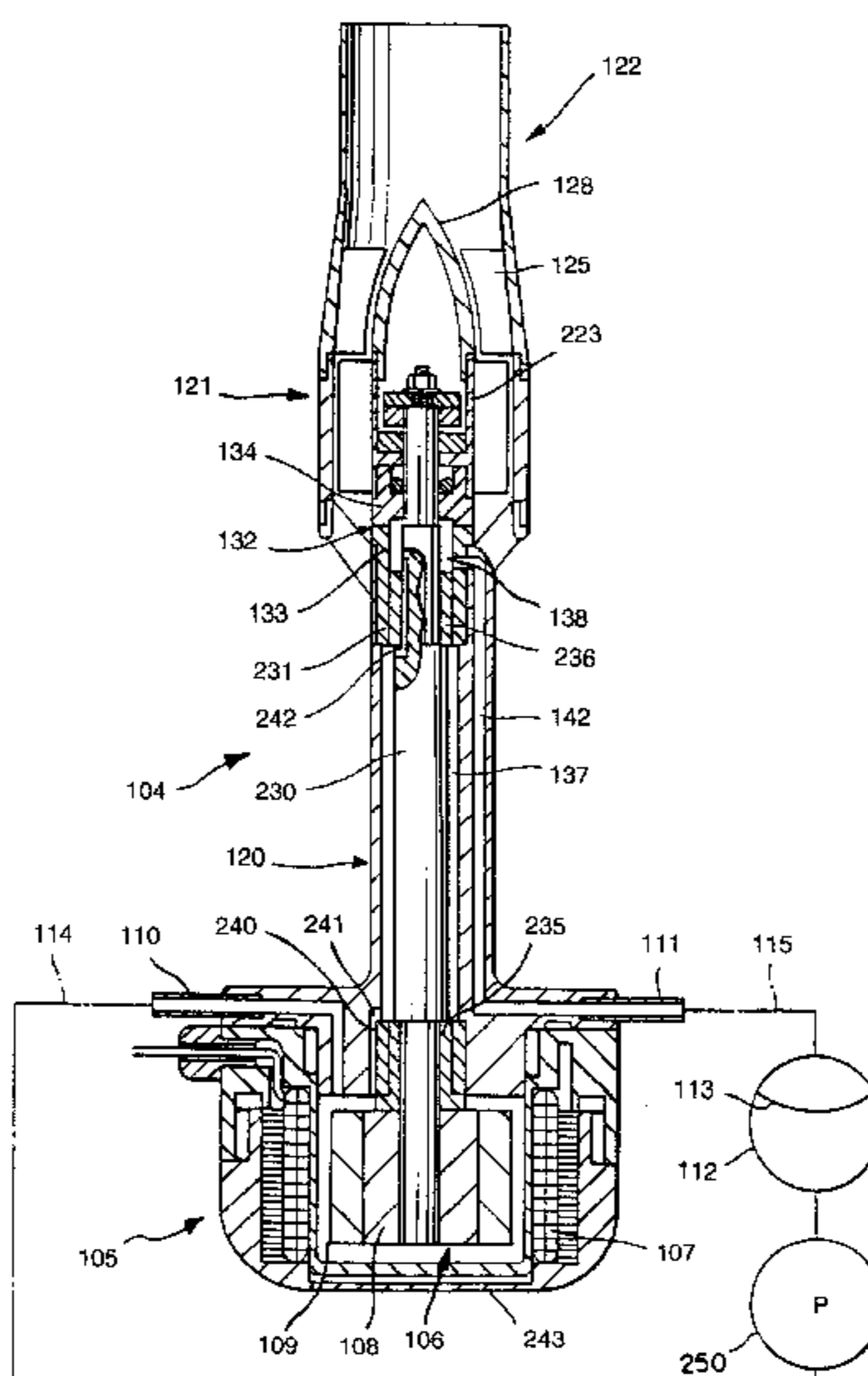
(30) **Foreign Application Priority Data**

Dec. 15, 1992 (JP) ..... 4-334589

(57) **ABSTRACT**

An artificial heart has a driving section, a nozzle section, a pump section for insertion into a ventricle of a human heart, and a sealing section forming a seal for a driving shaft extending from the driving section for driving the pump section. A sealing liquid chamber filled with a sealing liquid is formed around the driving shaft between the sealing mechanism and the driving section. The sealing liquid in the sealing liquid chamber maintains the sealing mechanism in a liquid-tight state and lubricates the sealing mechanism, whereby blood is prevented from entering the driving section. Even if blood happens to enter the driving section, the blood is mixed with the sealing liquid and does not coagulate. Thus, the operation of the artificial heart is not suppressed.

**11 Claims, 18 Drawing Sheets**



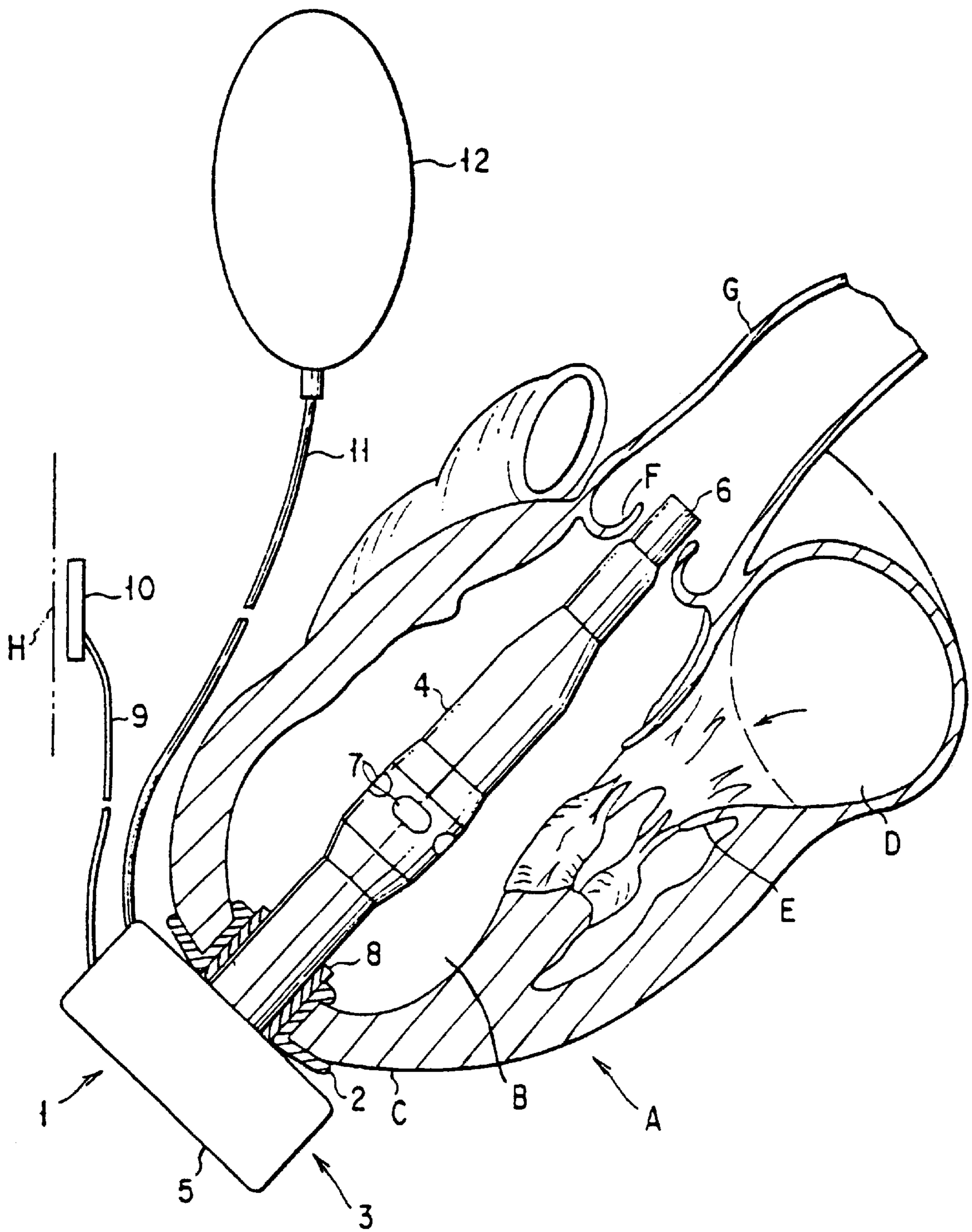


Fig. 1

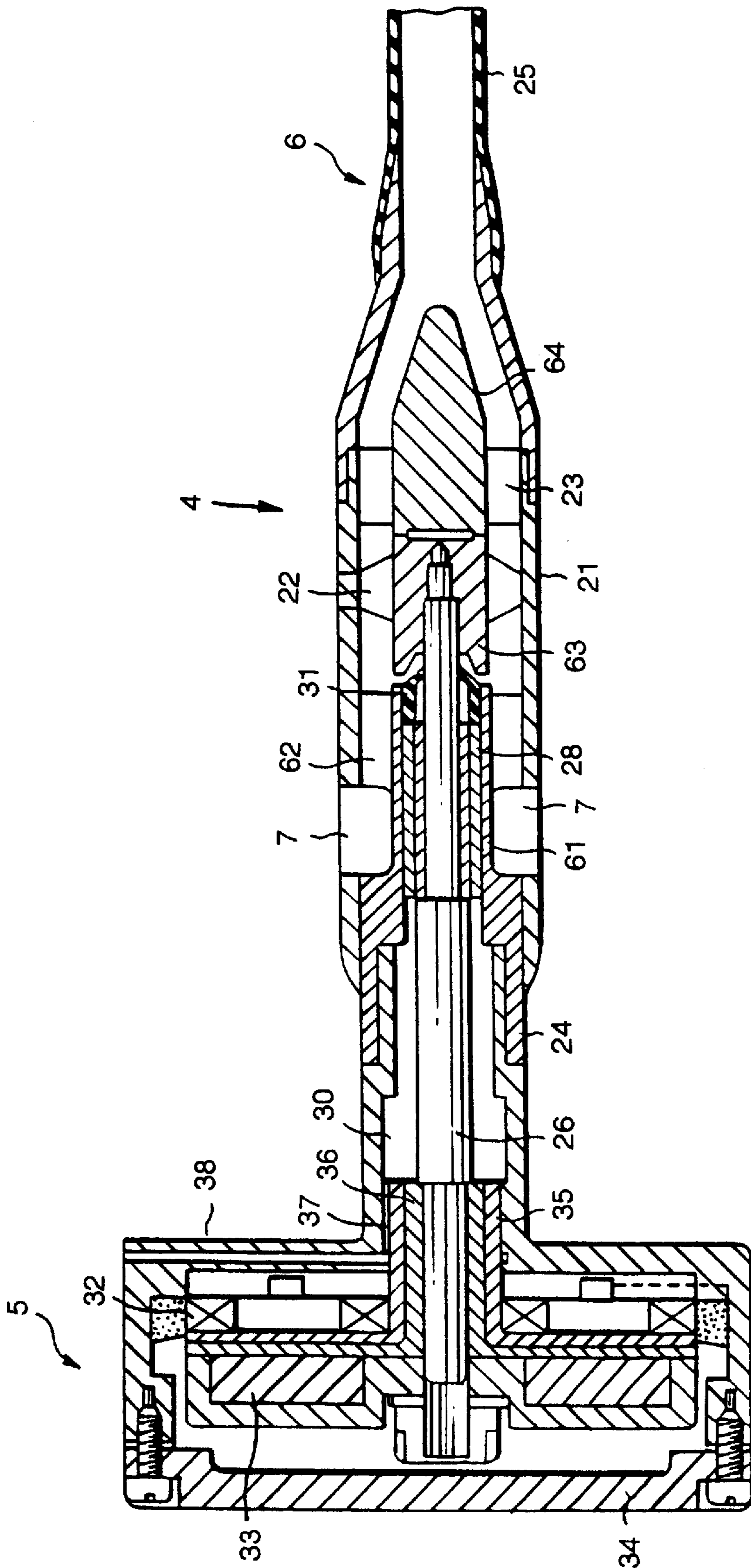


Fig. 2

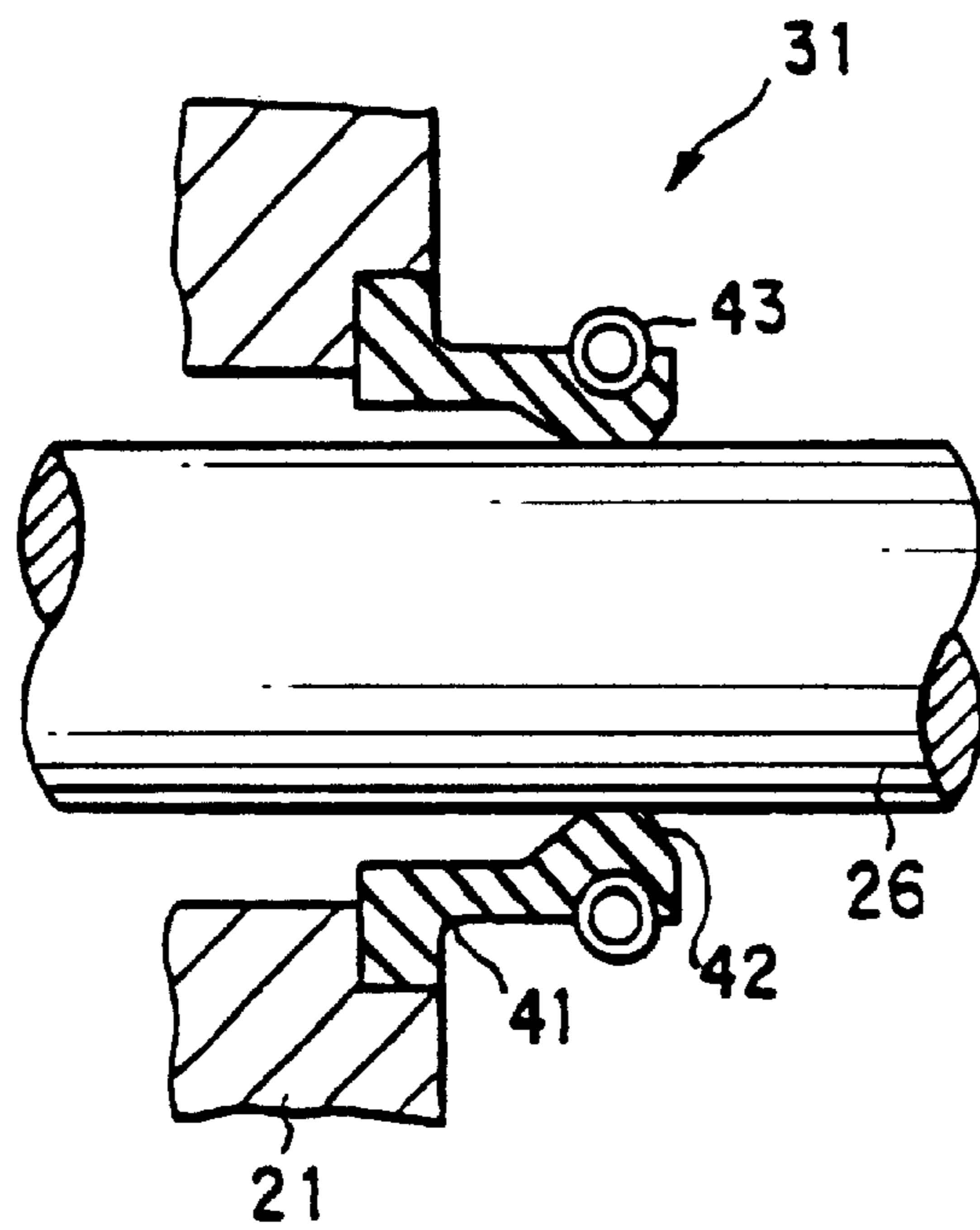


Fig. 3

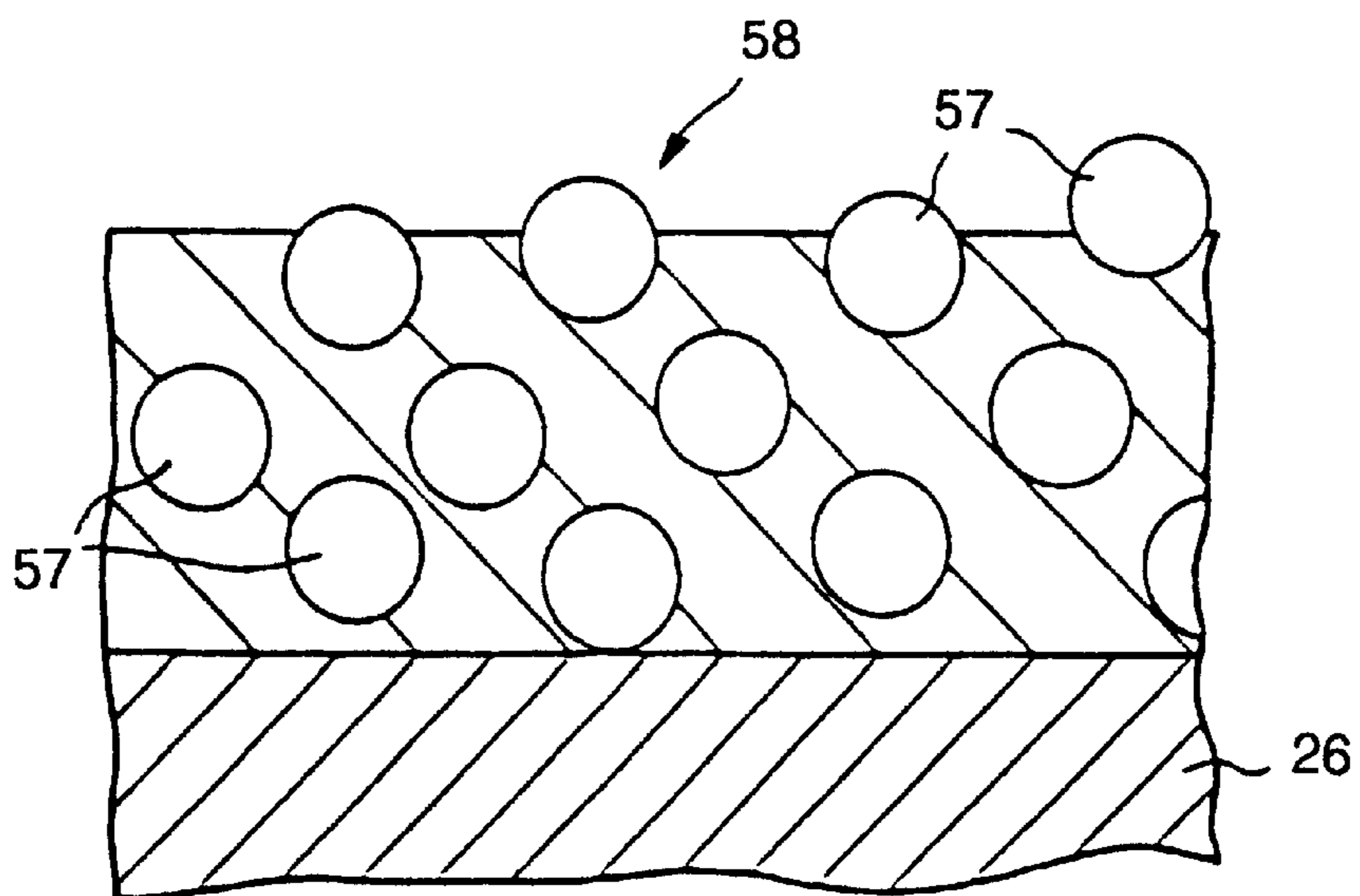


Fig. 4



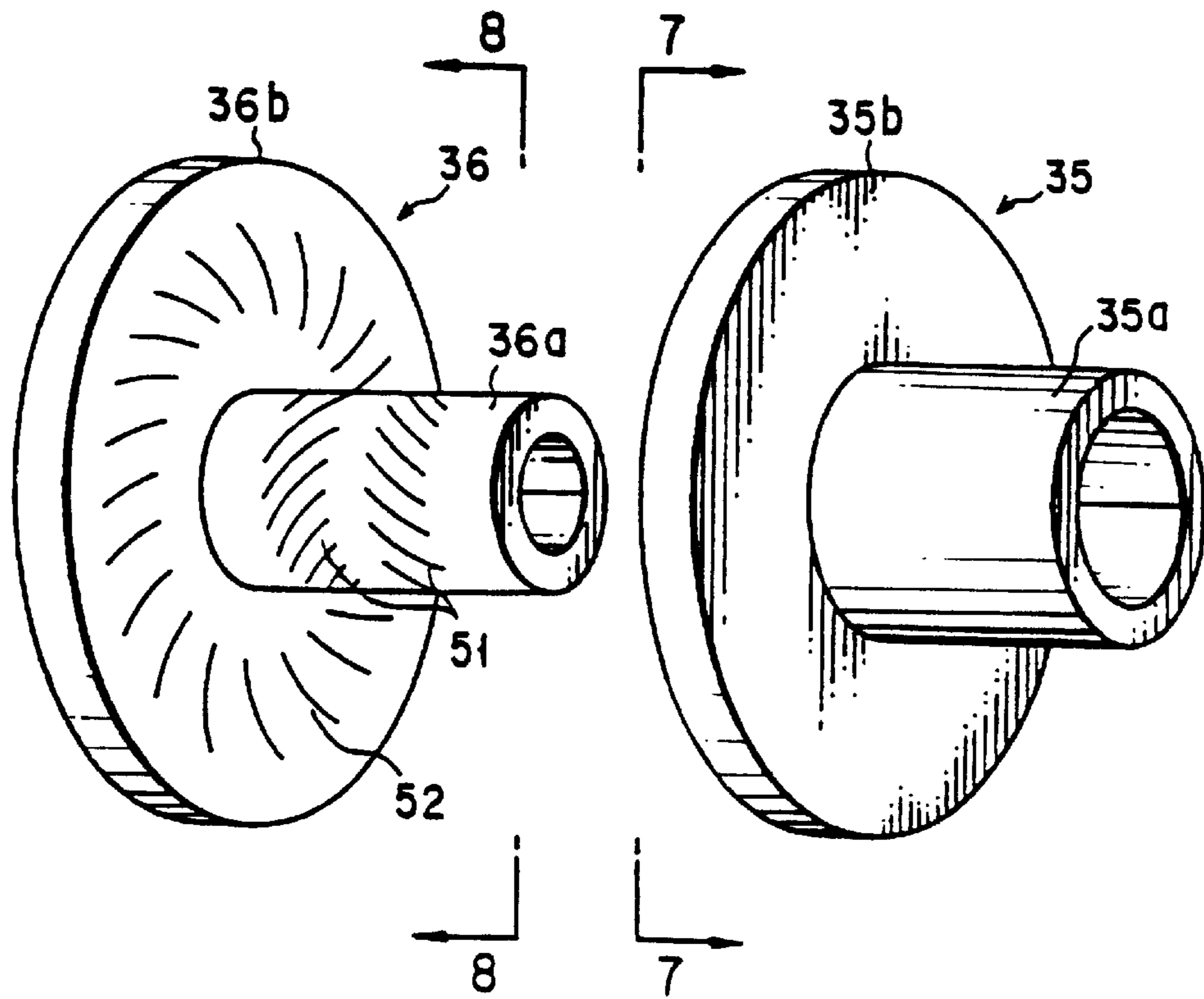


Fig. 5

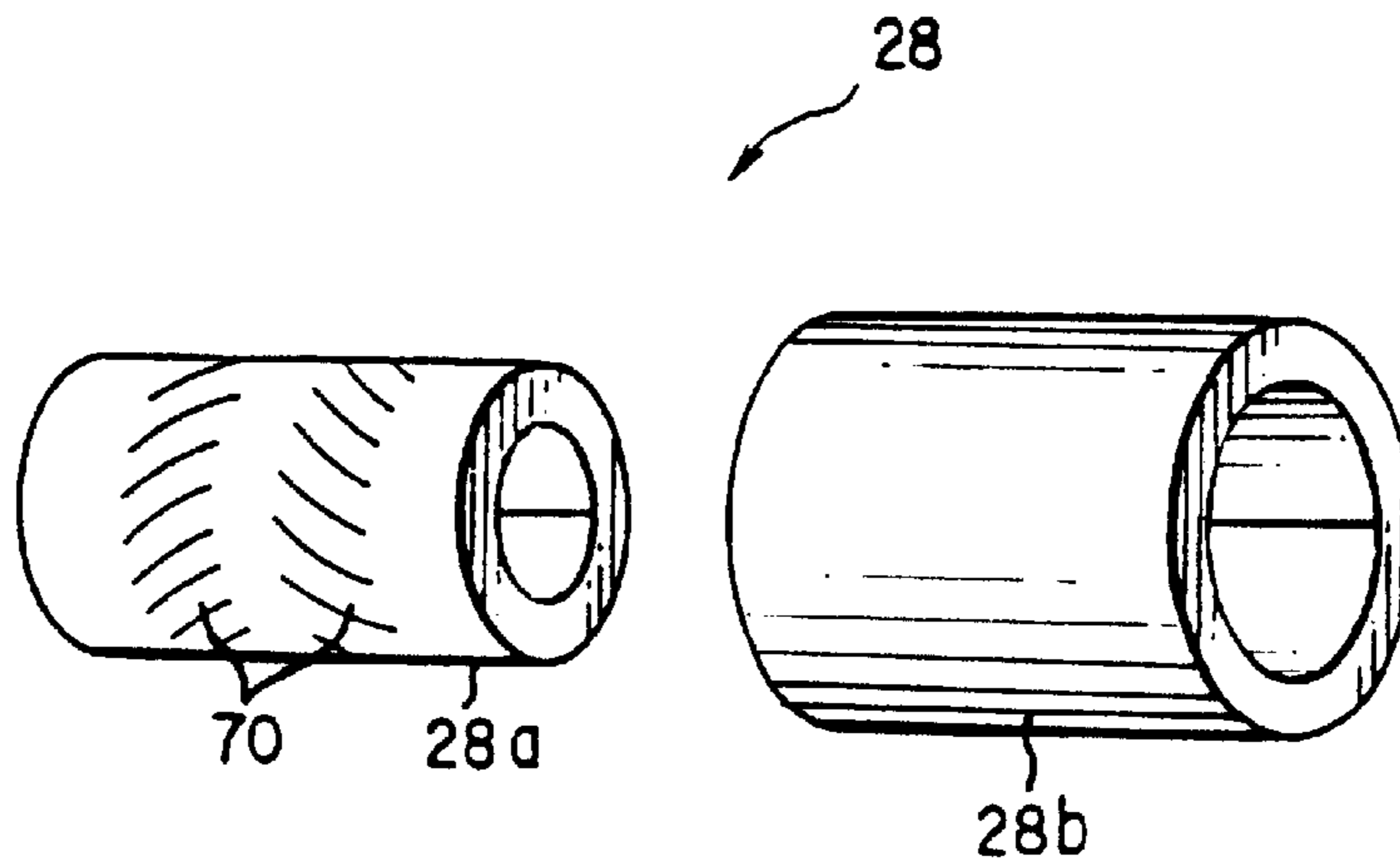


Fig. 6

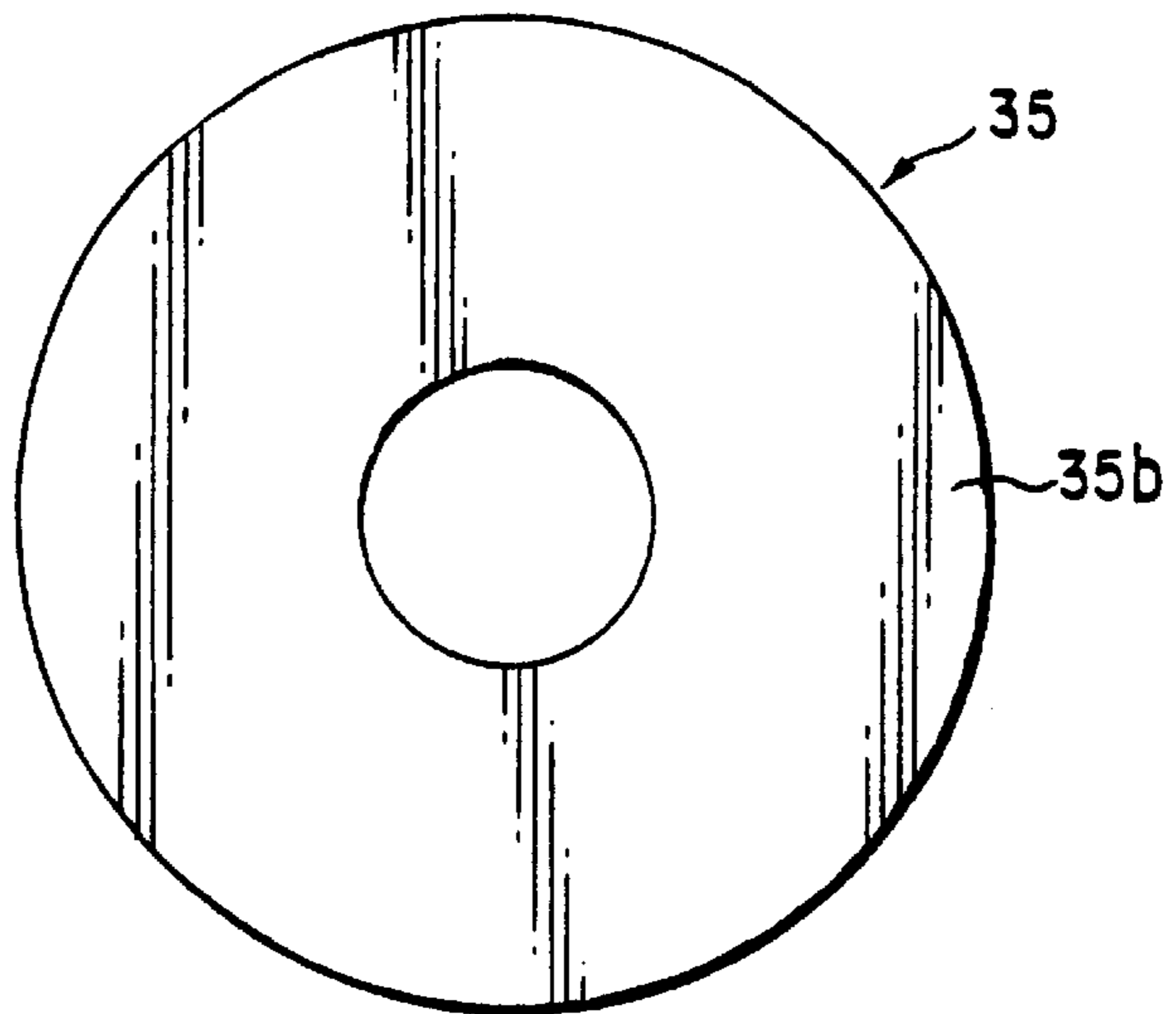


Fig. 7

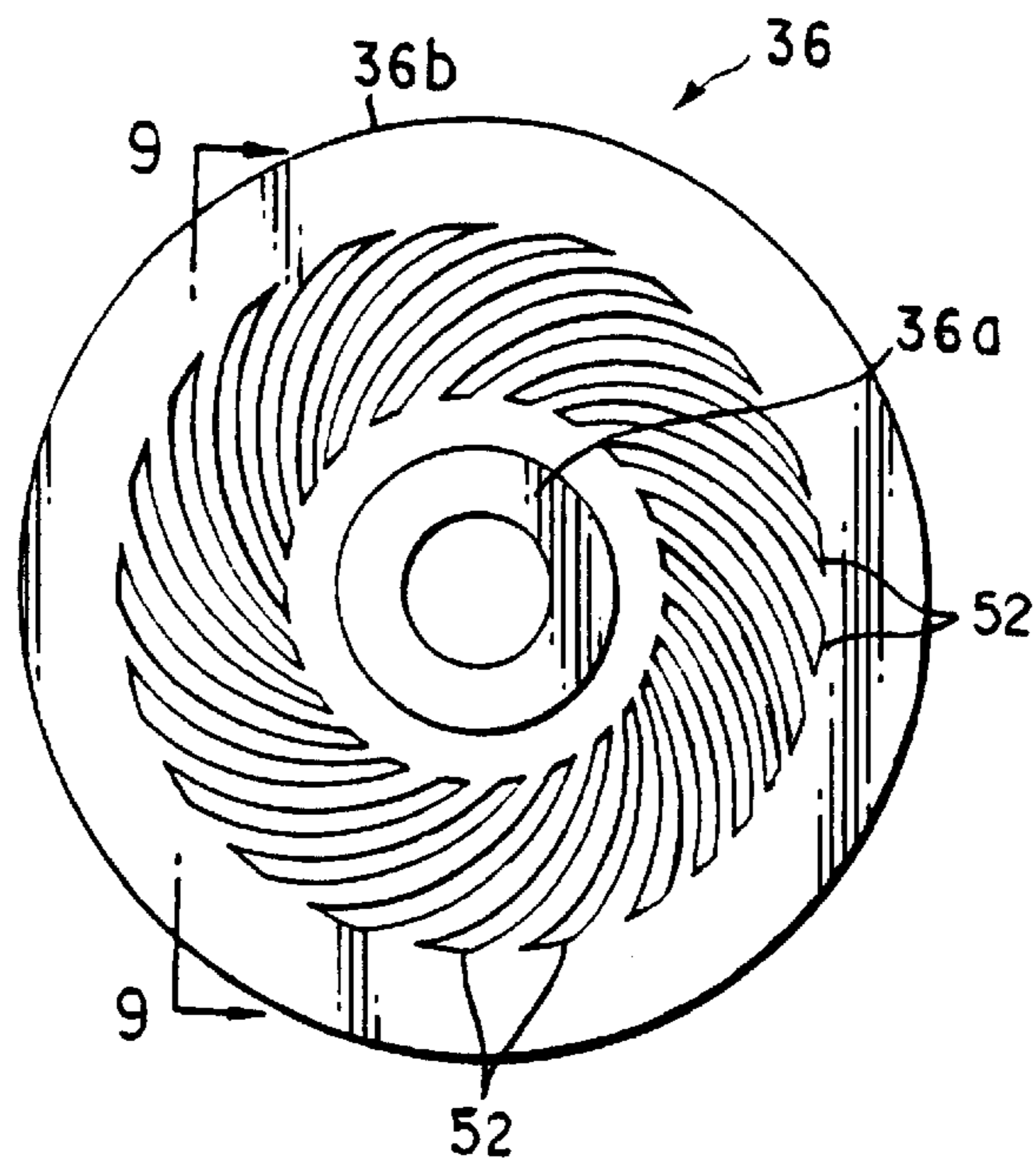


Fig. 8

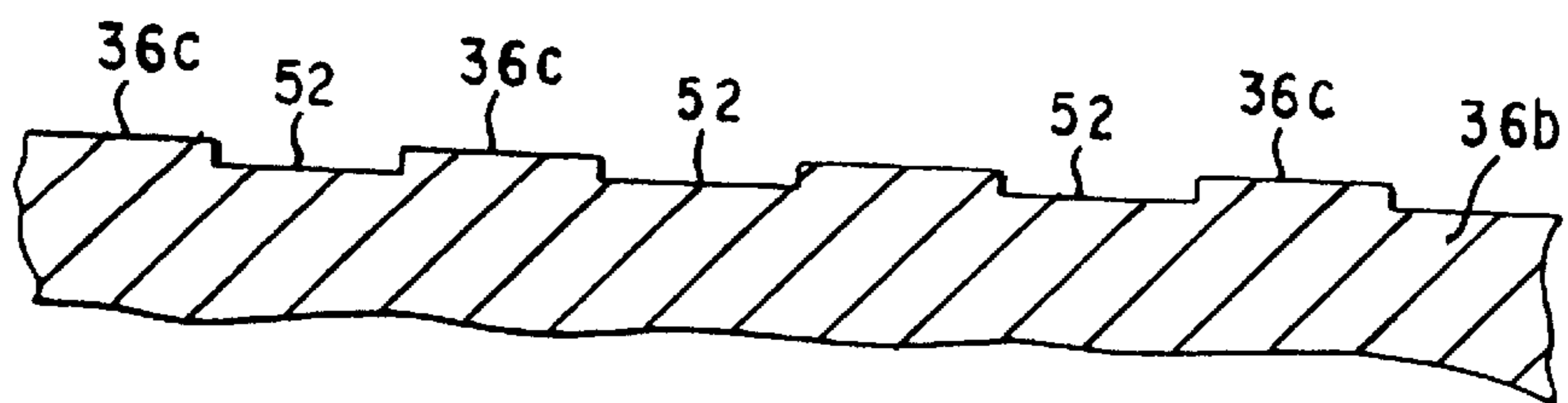


Fig. 9

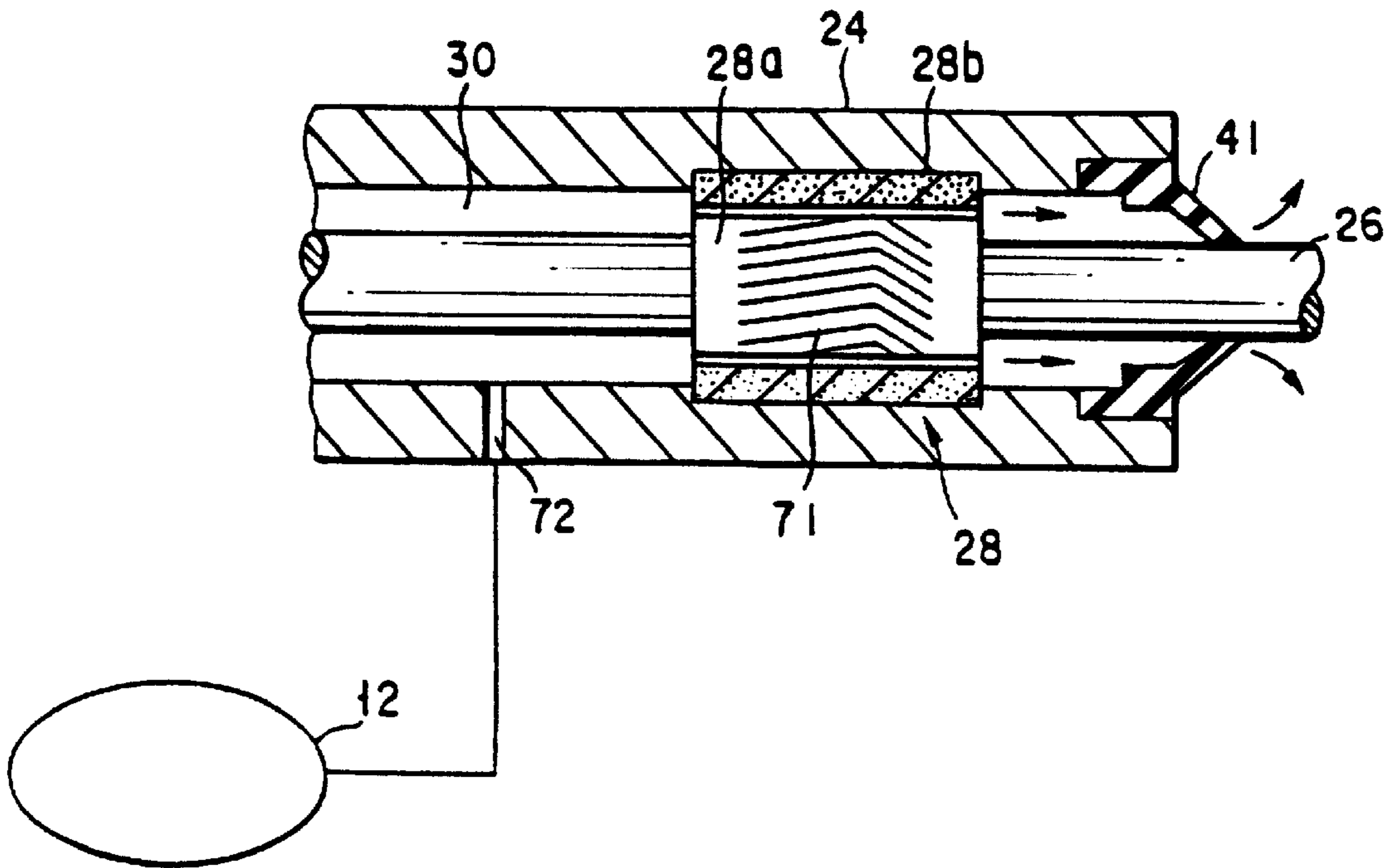


Fig. 10

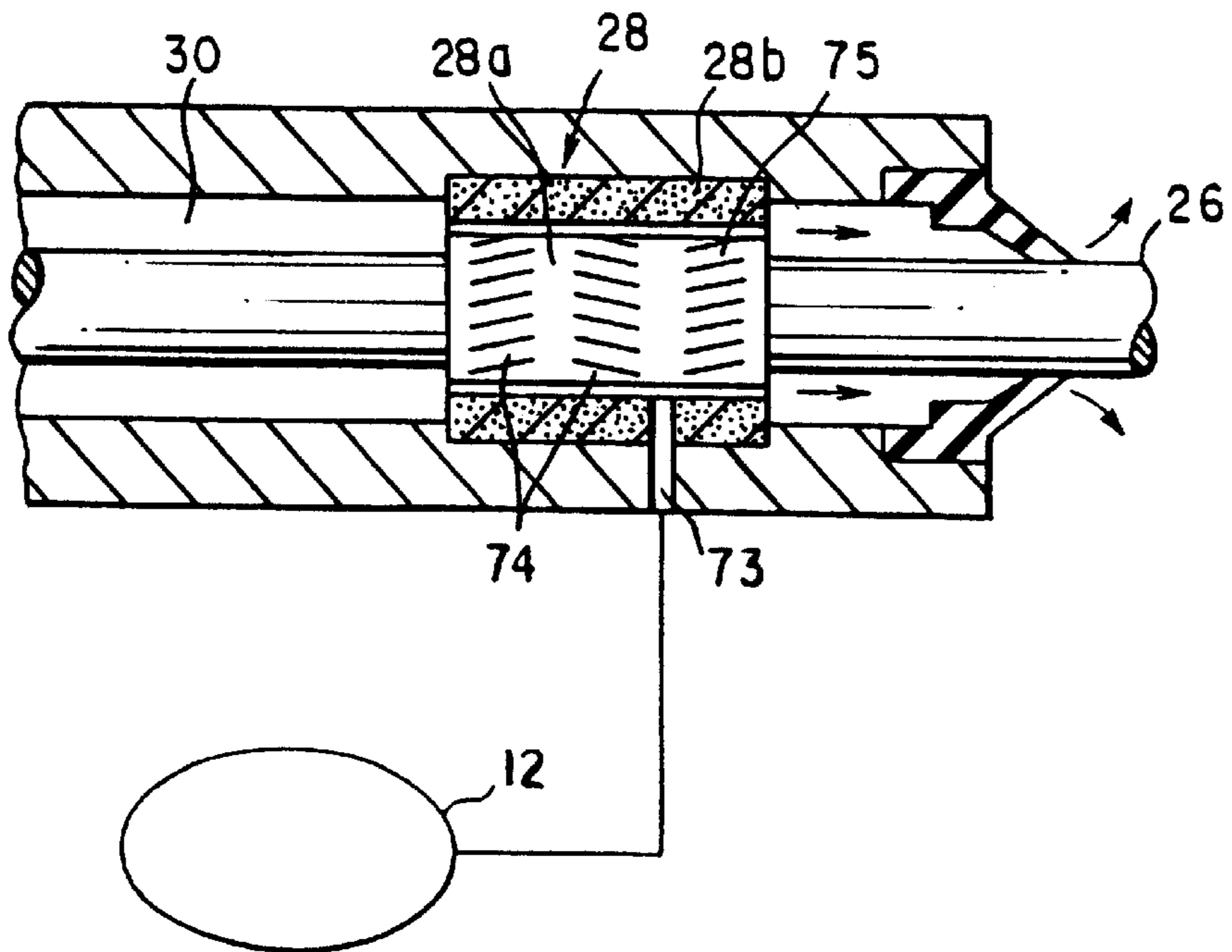


Fig. 11

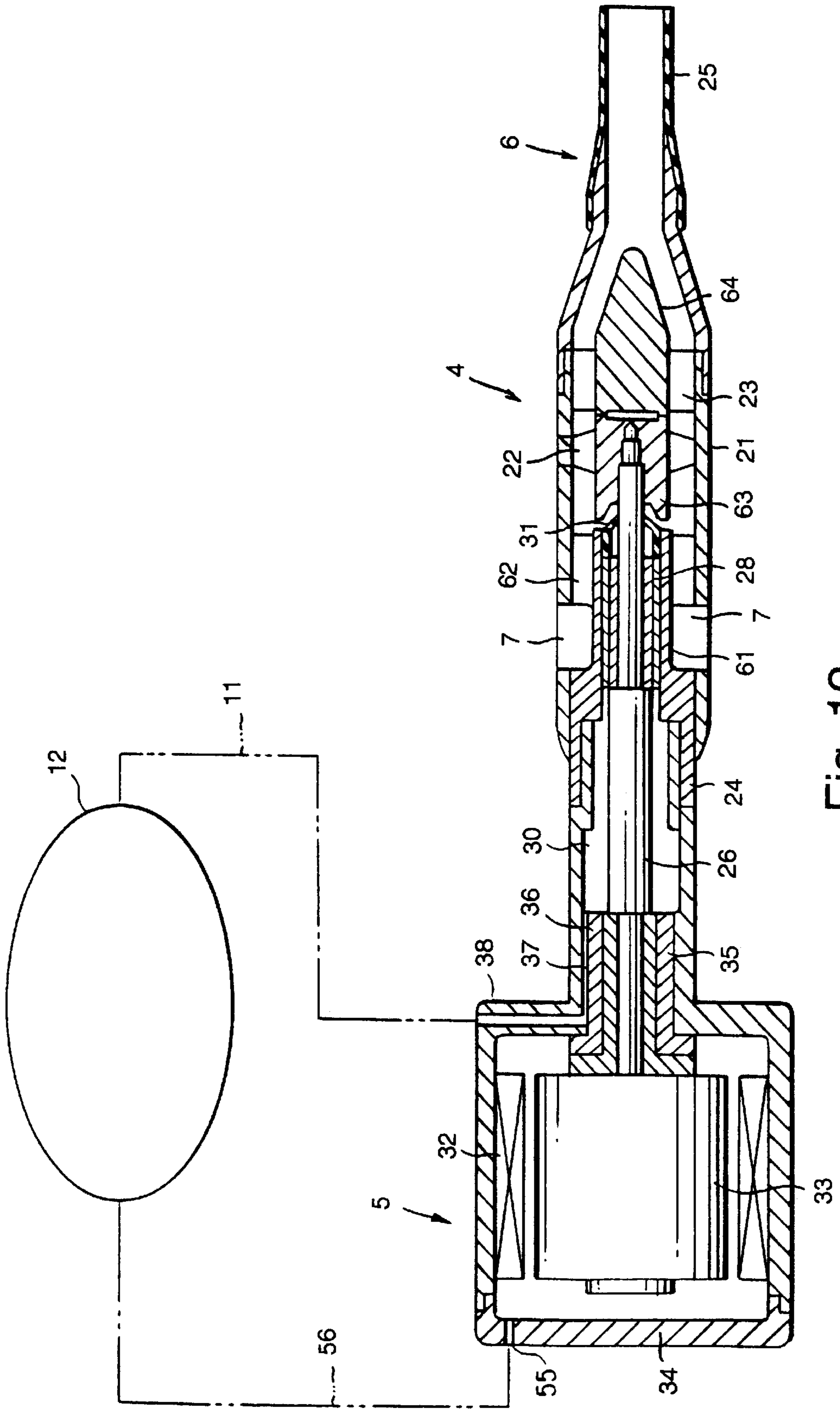


Fig. 12





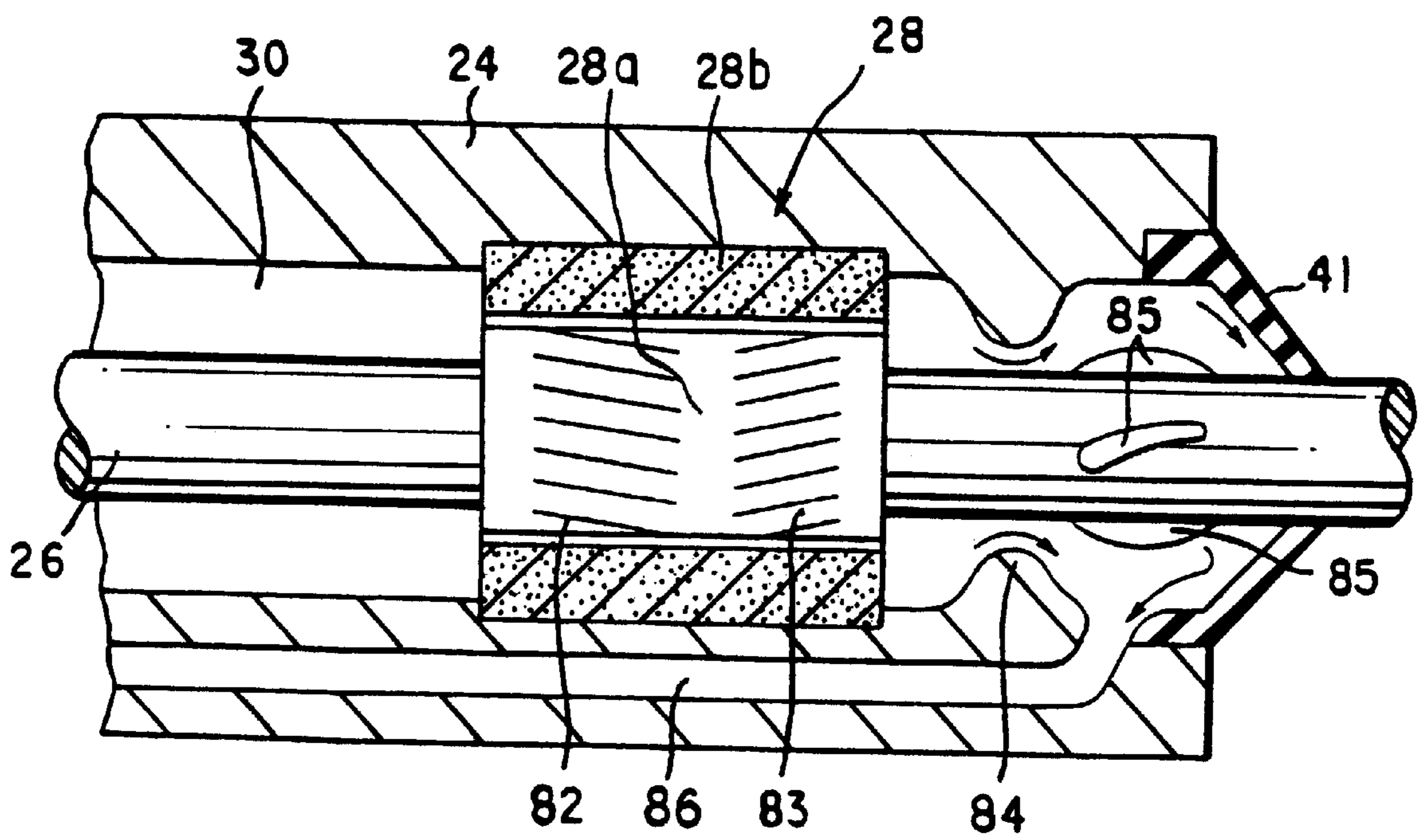


Fig. 14

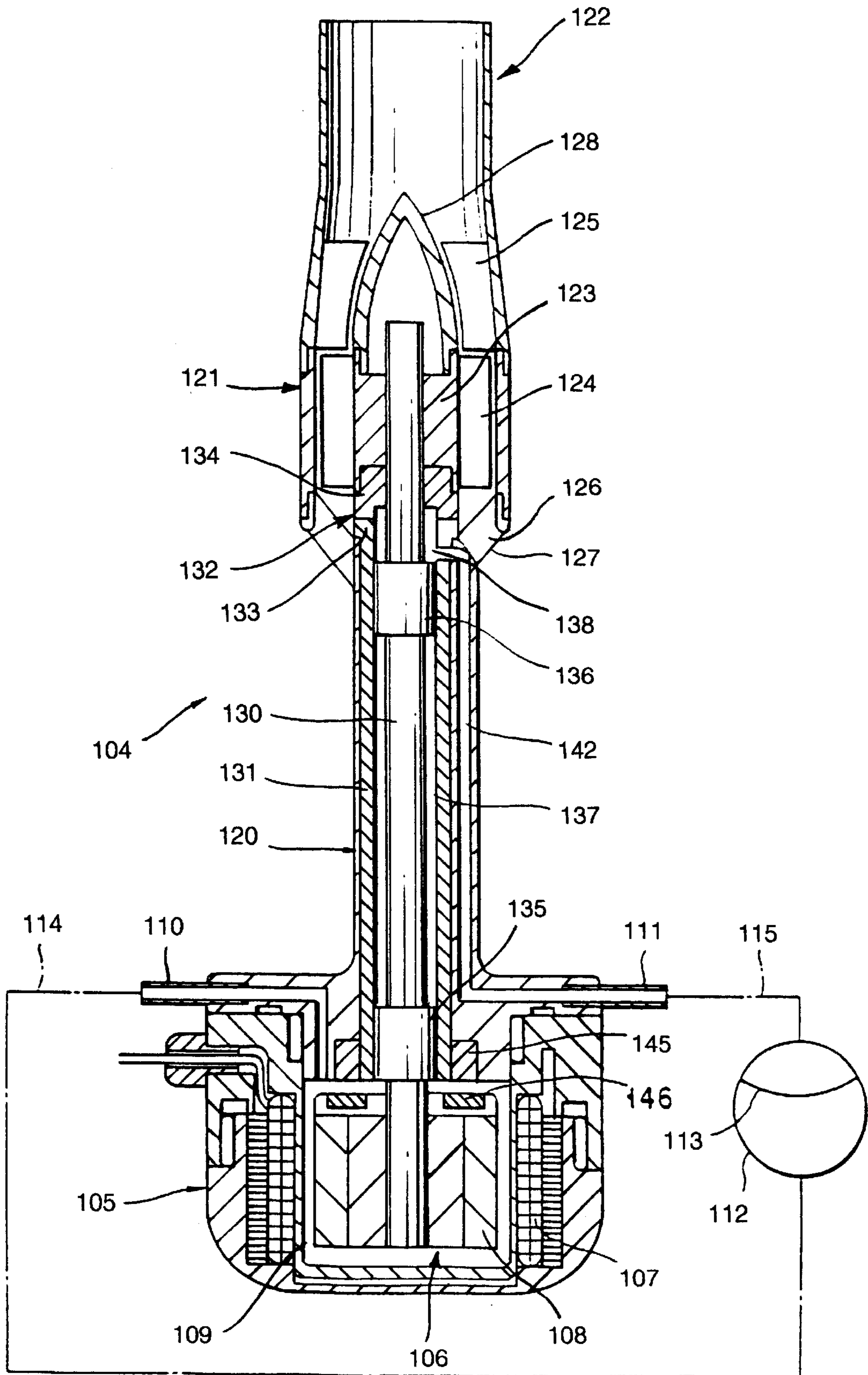


Fig. 15

Fig. 16

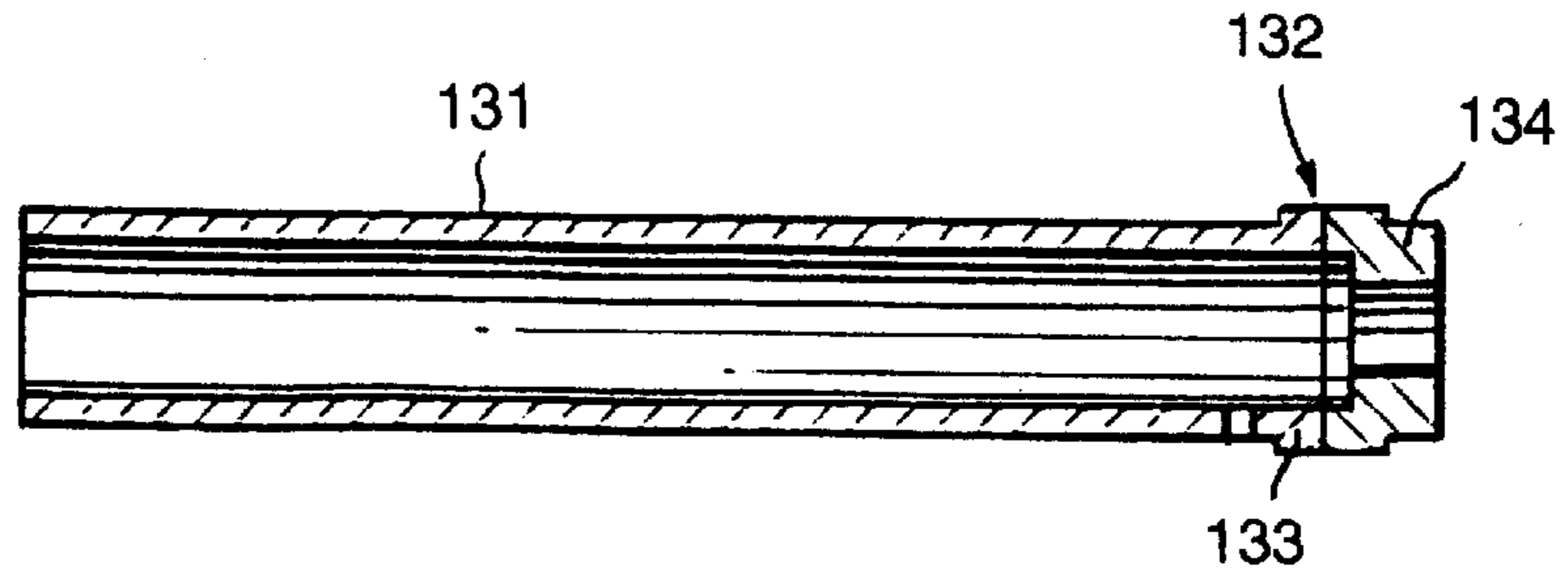


Fig. 17

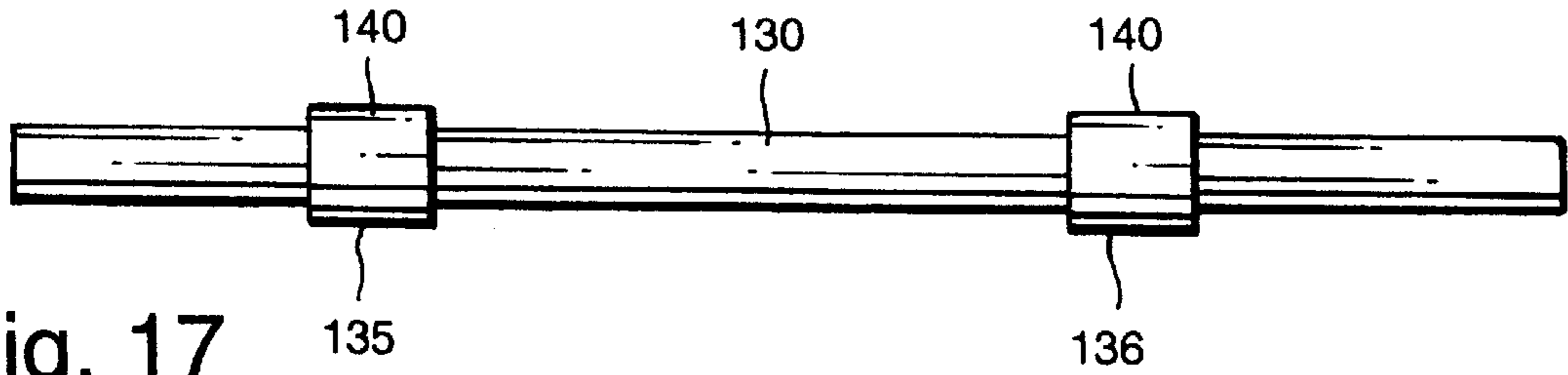


Fig. 19

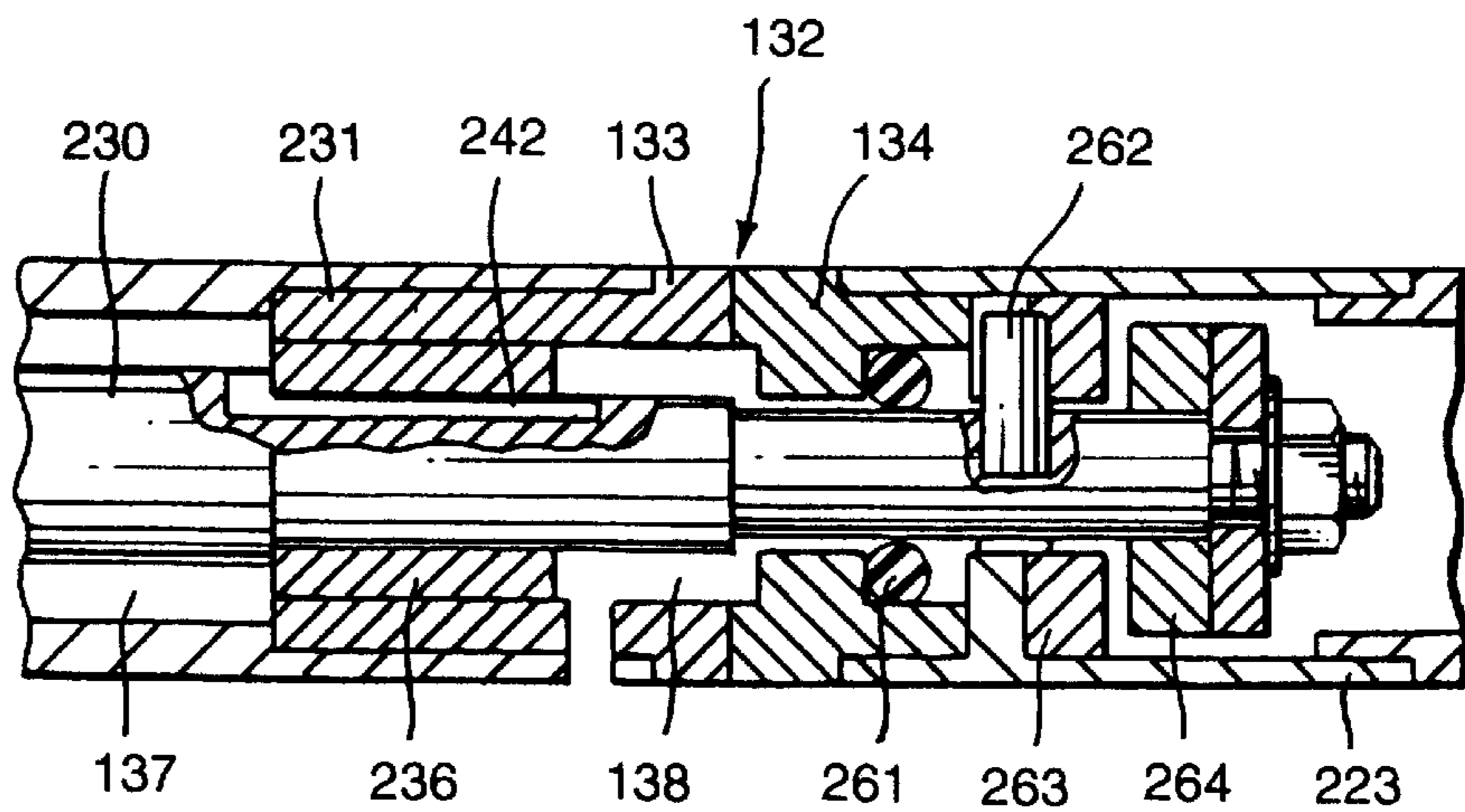
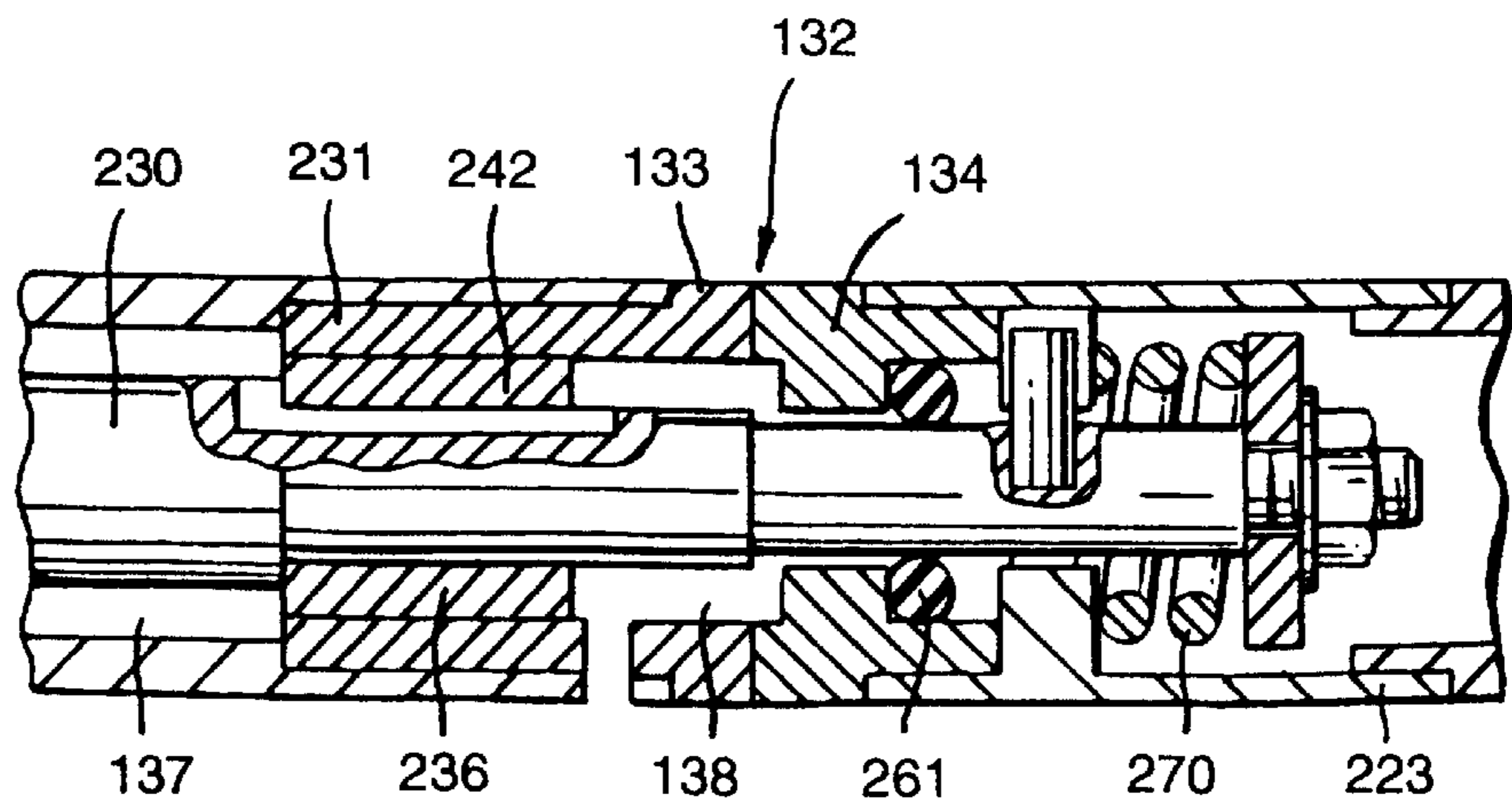


Fig. 20











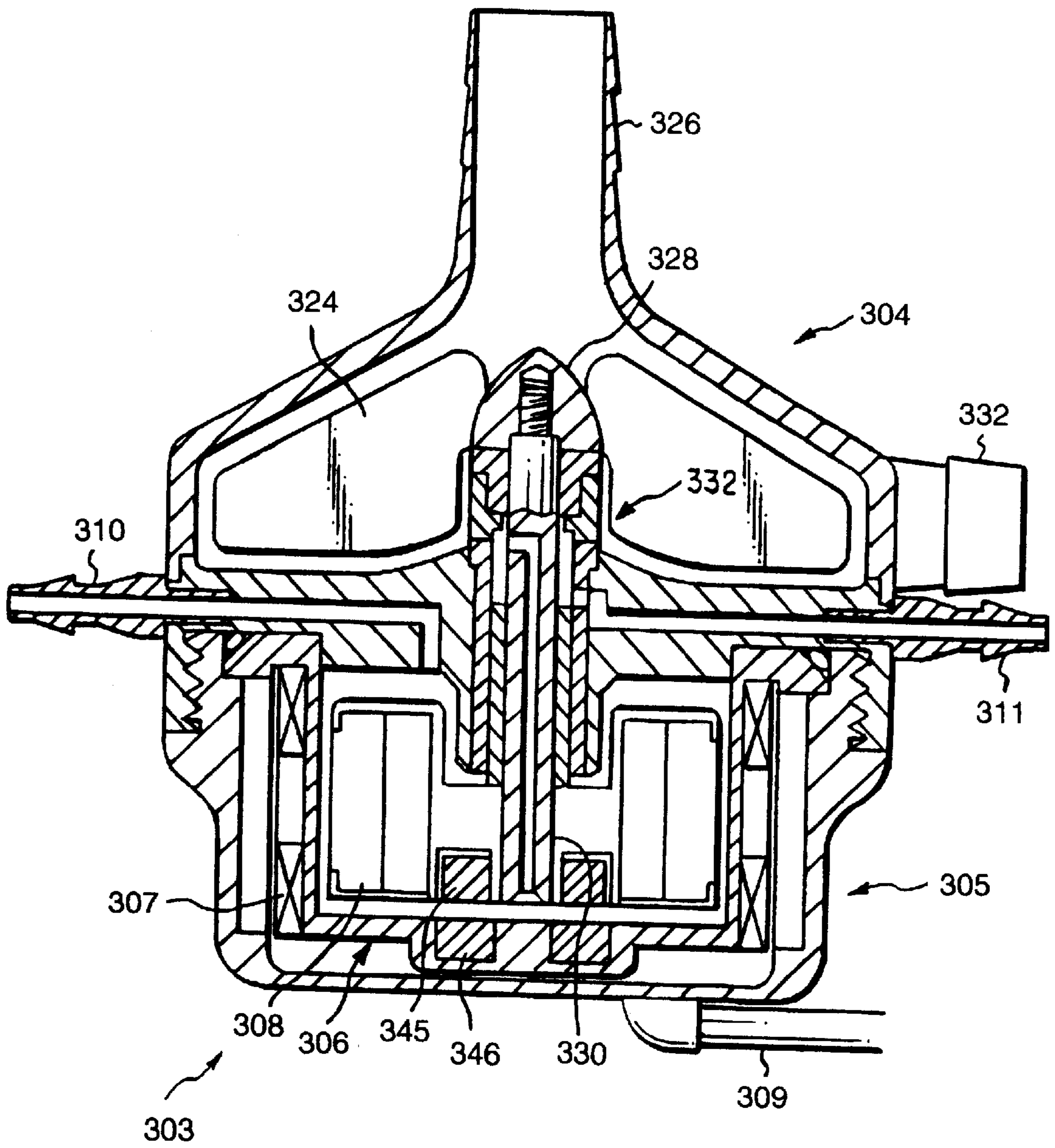


Fig. 23



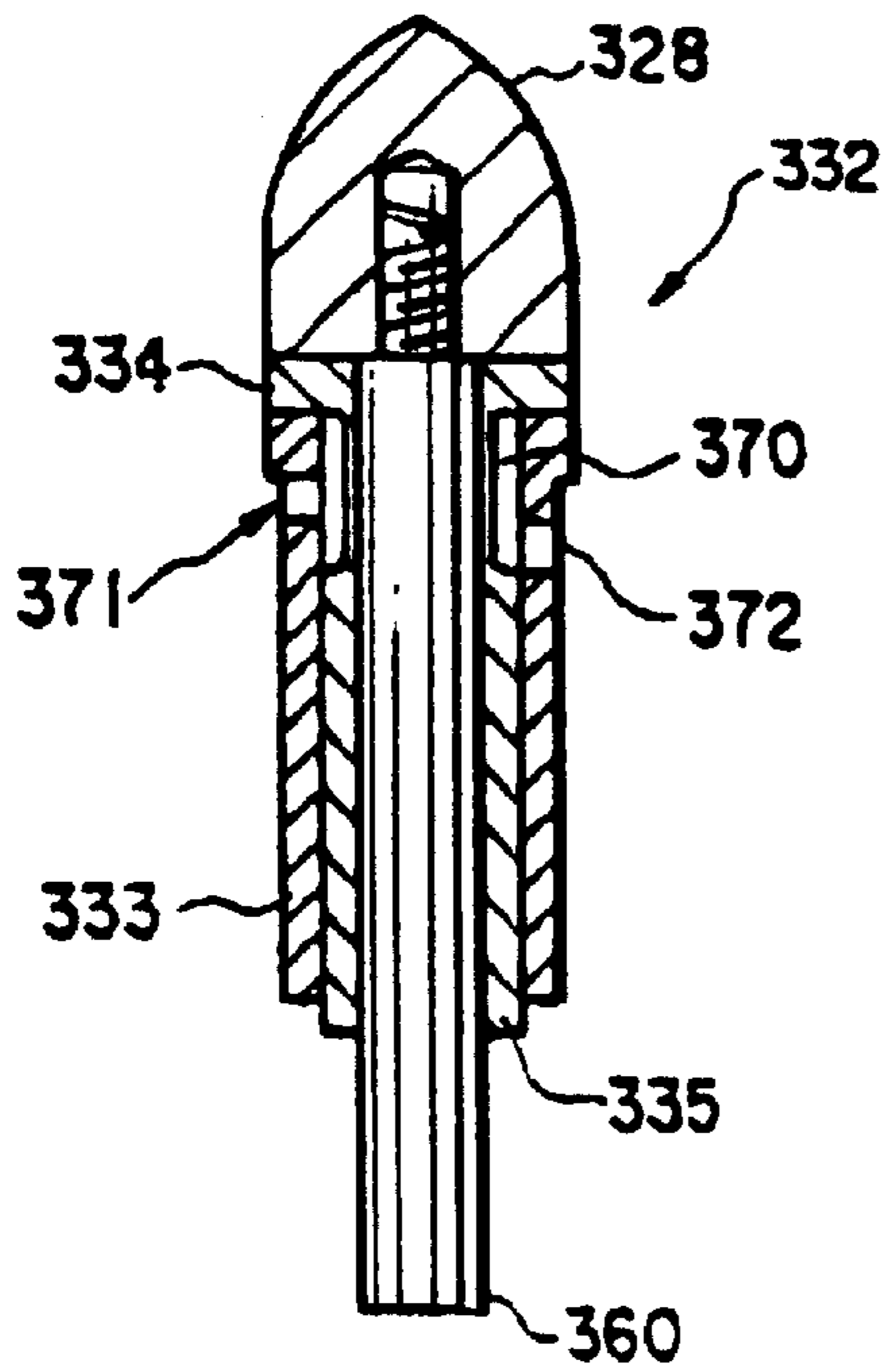


Fig. 24

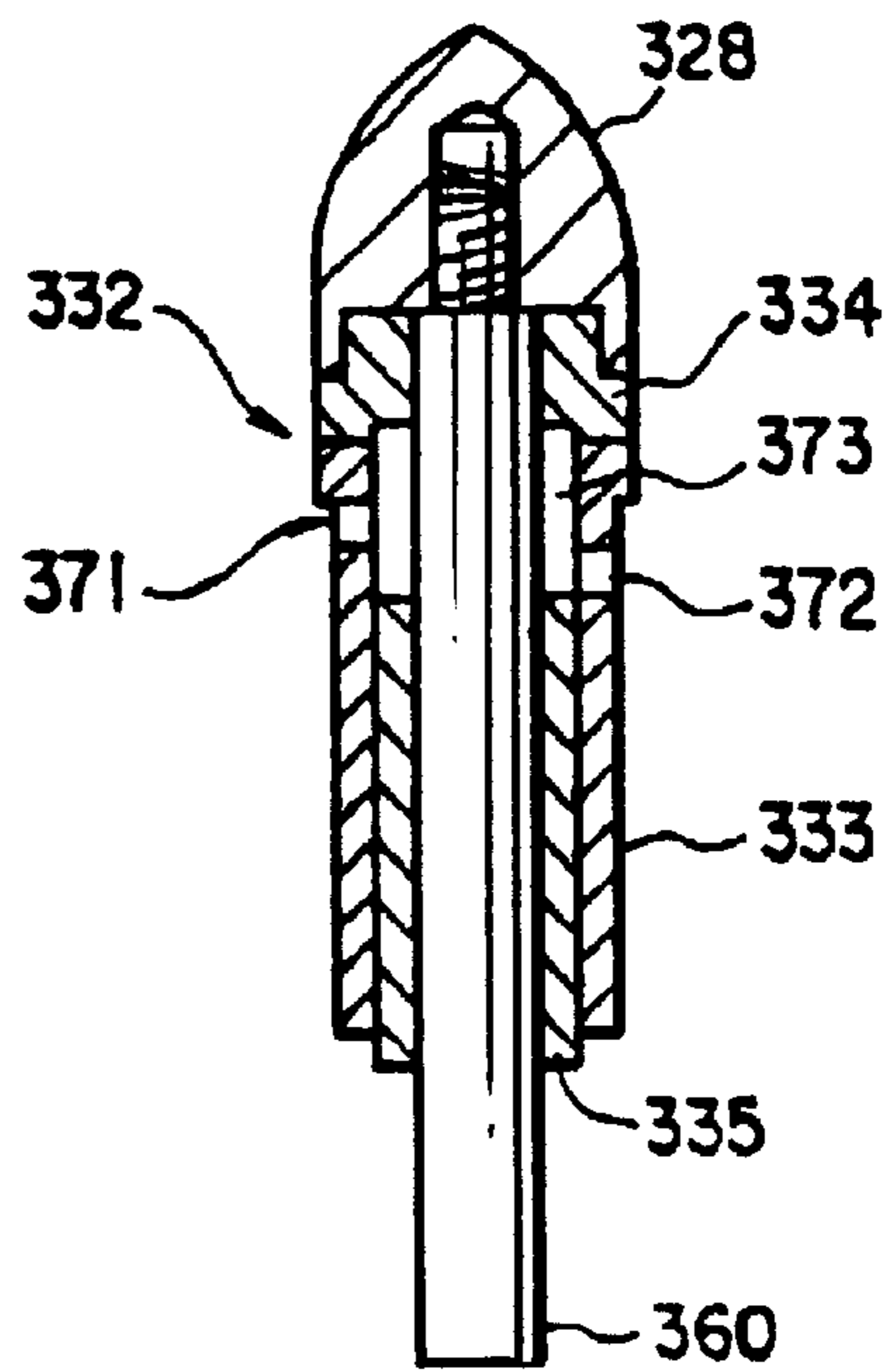


Fig. 25

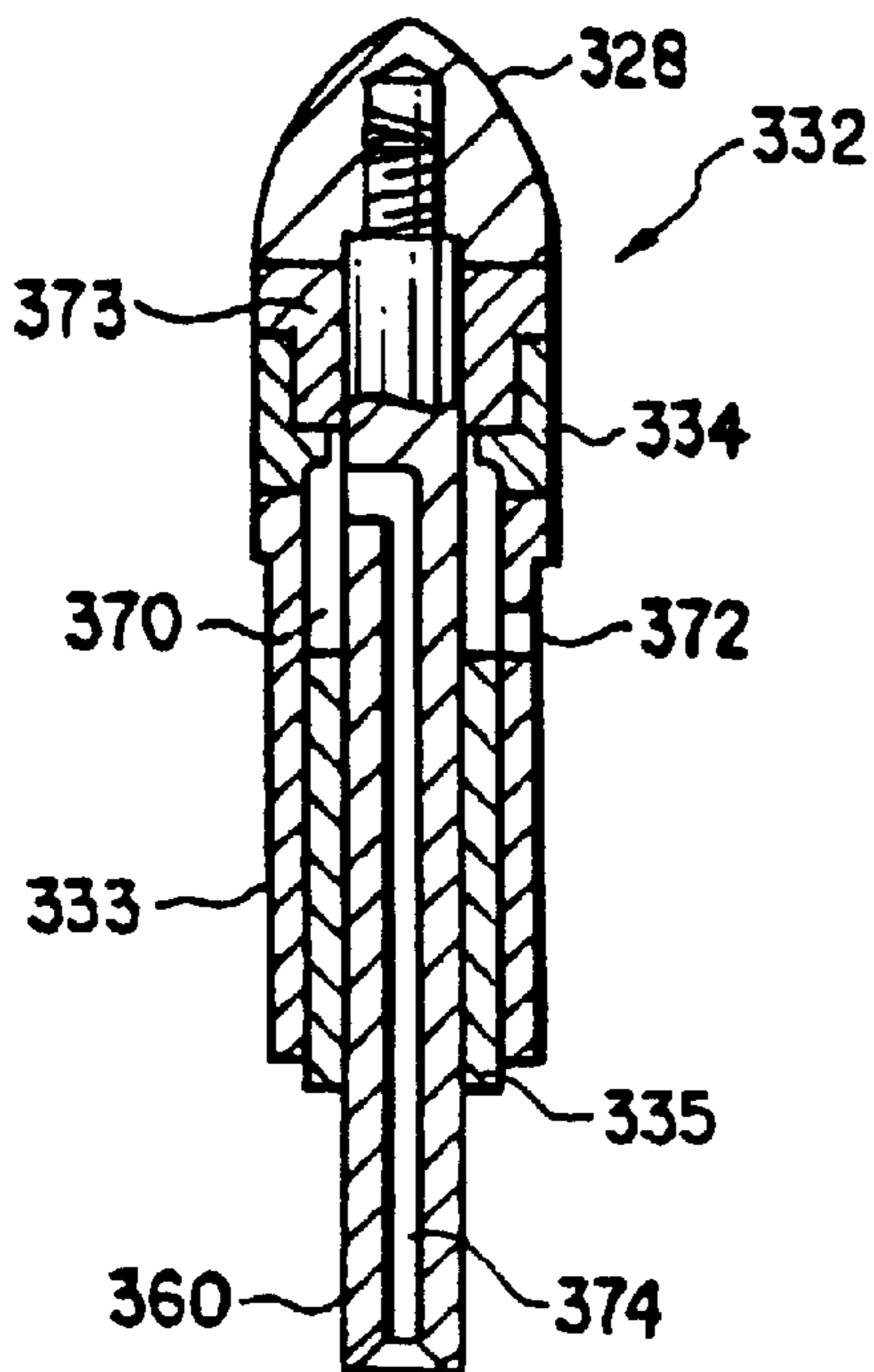


Fig. 26

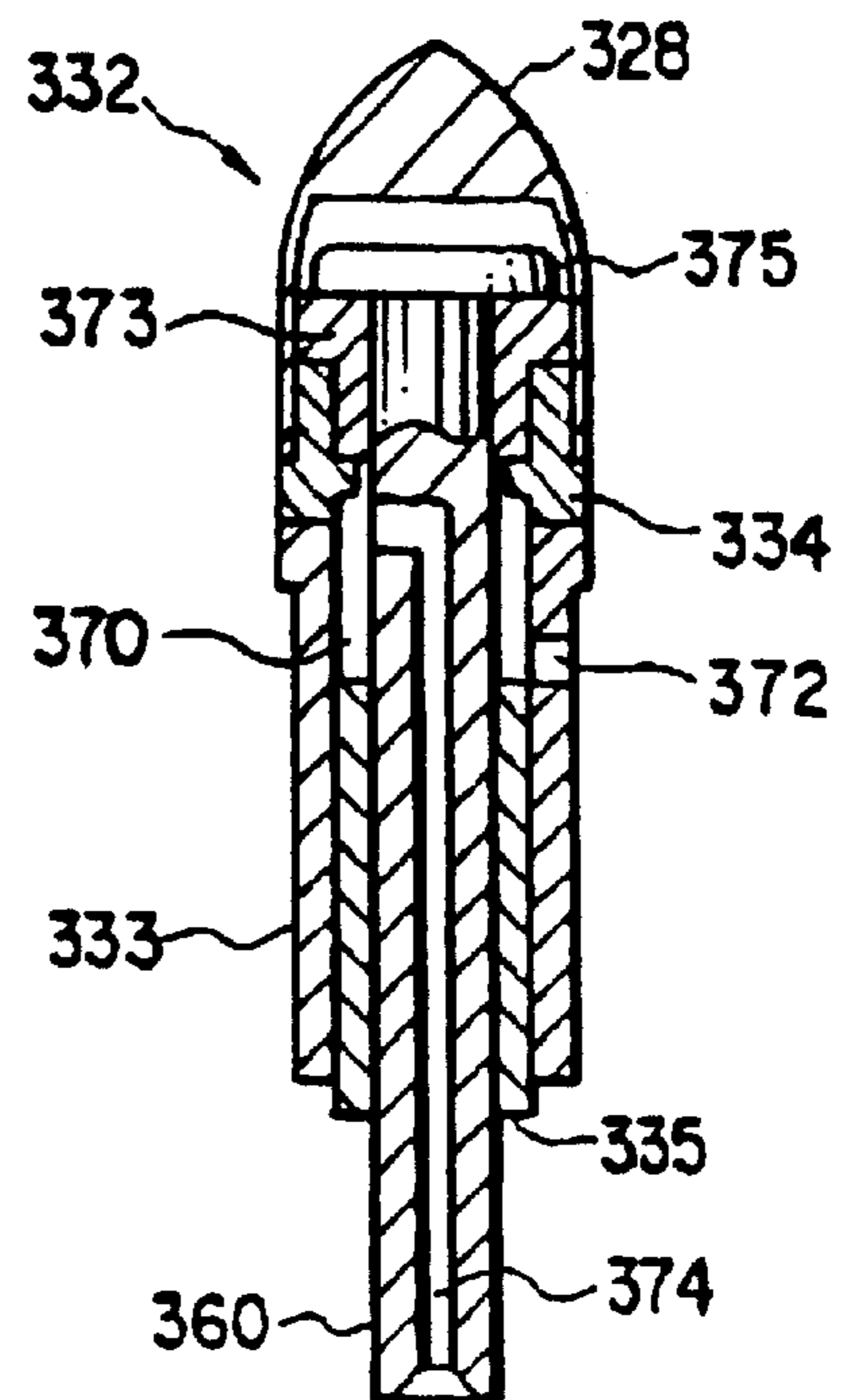


Fig. 27

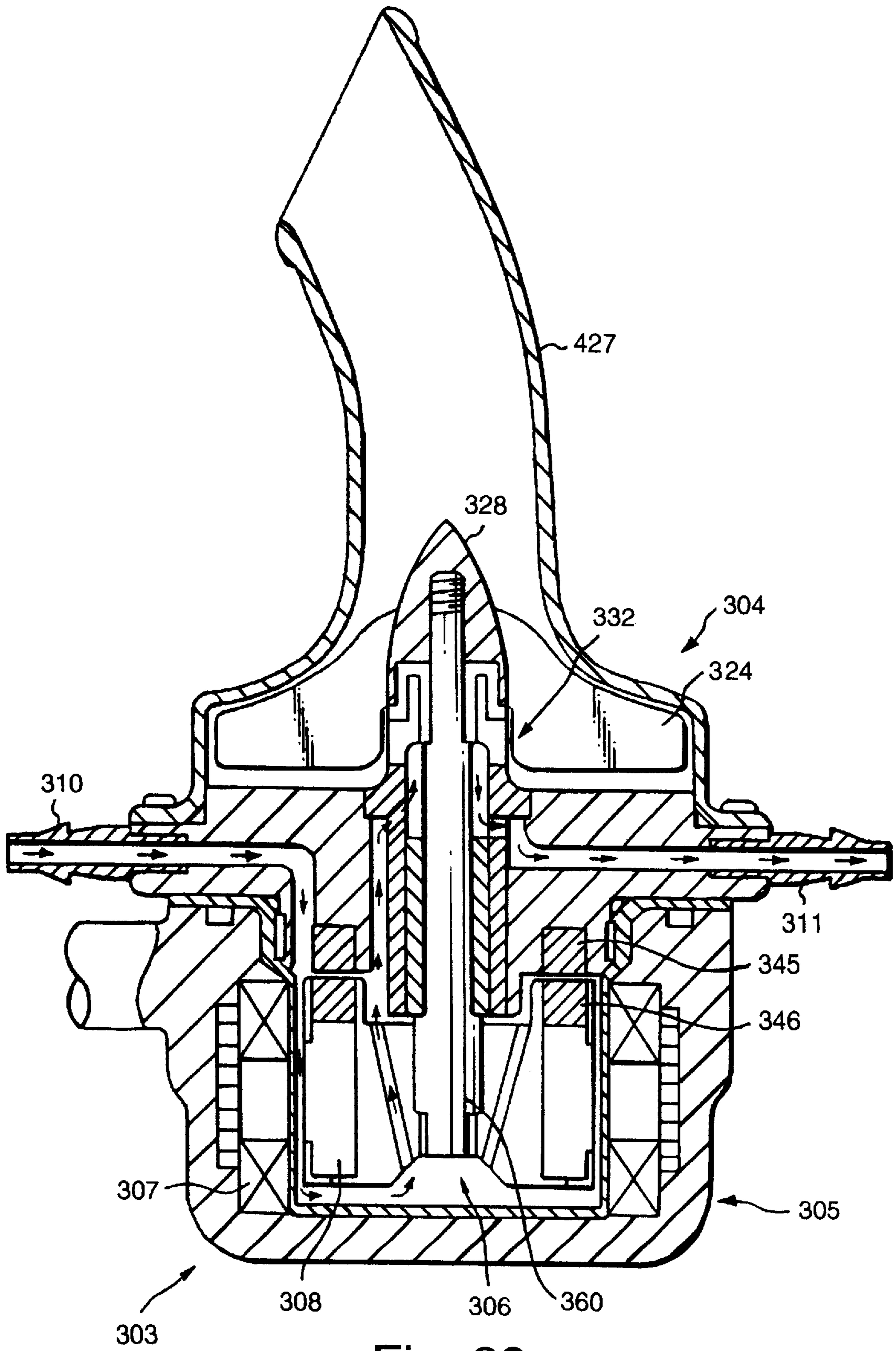


Fig. 28

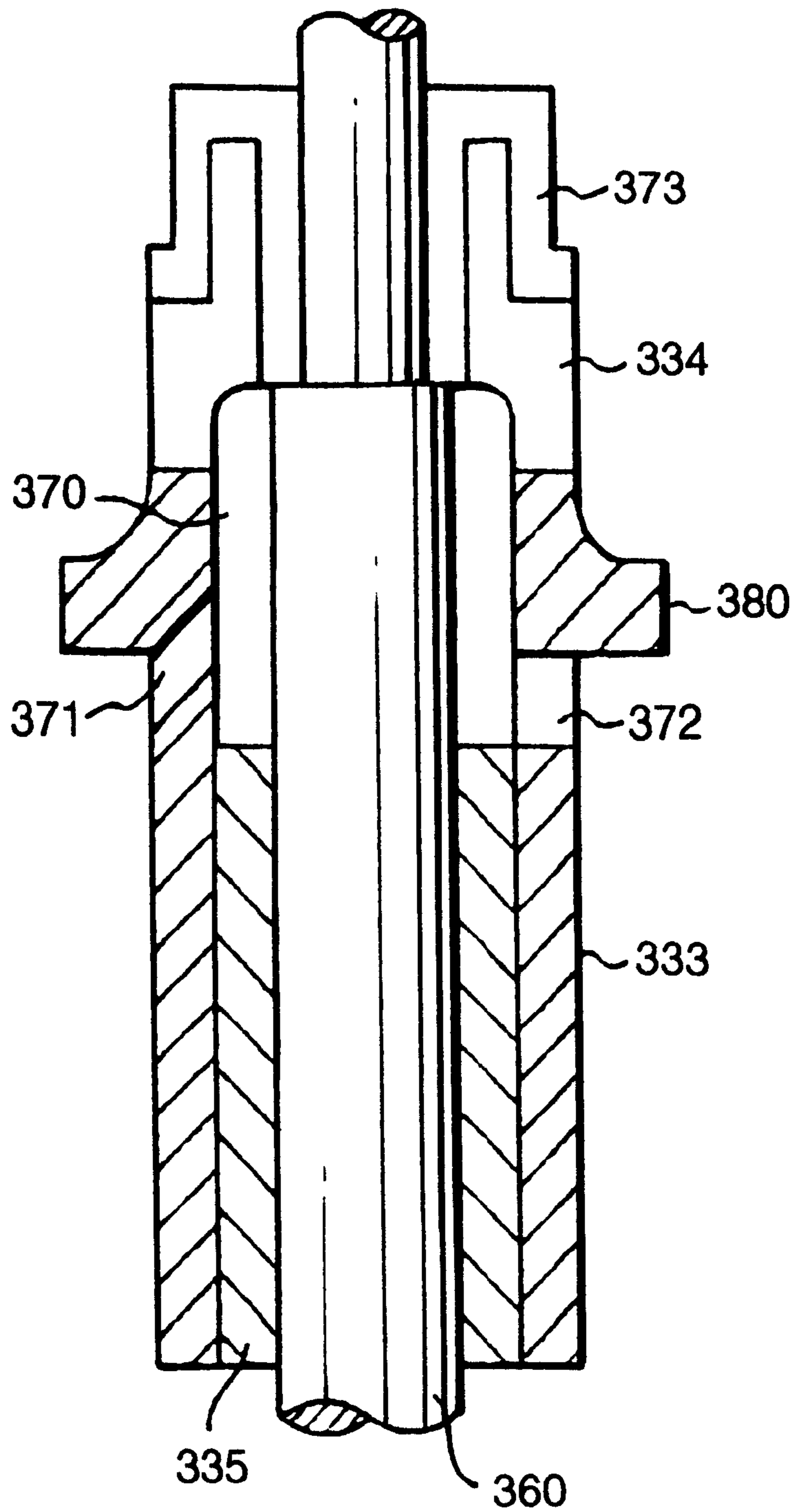


Fig. 29



## AUXILIARY ARTIFICIAL HEART OF AN EMBEDDED TYPE

### RELATED APPLICATIONS

This a divisional of application Ser. No. 09/469,290, filed Dec. 22, 1999, now U.S. Pat. No. 6,302,910, which is a divisional of application Ser. No. 08/603,193, filed Feb. 20, 1996, now abandoned, which is a continuation-in-part of application Ser. No. 08/505,784, filed Jul. 21, 1995, now abandoned, which is a continuation-in-part of application Ser. No. 08/079,817, filed Jun. 22, 1993, now abandoned, the disclosures of which are incorporated herein by reference.

### BACKGROUND OF THE INVENTION

#### 1. Field of the Invention

This invention relates to an auxiliary artificial heart of an embedded type, embedded in the left or right ventricle of the heart in a human body, and more particularly to an artificial heart operated at high reliability by preventing body fluids such as blood from adversely entering the artificial heart.

#### 2. Description of the Related Art

Conventional artificial hearts are of the diaphragm type, sack type, axially symmetric type, centrifugal type, of pusher plate type or the like. Each of these conventional artificial hearts delivers blood in place of a human heart or by bypassing it.

Recently, an auxiliary artificial heart has been developed which is embedded in a ventricle of a human heart and has the tip end of a nozzle passing through an aorta valve or the like such that blood is delivered from the ventricle into an aorta through the nozzle. The artificial heart does not suppress any function of the human heart when it is installed in the human heart and it delivers additional blood into the aorta when blood pumped out from the human heart is insufficient. The blood is delivered not only by the artificial heart but also by the pulsing or beating of the human heart. Even if the operation of the artificial heart happens to stop, blood is delivered to the body by beating of the human heart.

Naturally, the volume of the part of the artificial heart which is inserted in a ventricle of the human heart must be smaller than the volume of the human heart when it is fully contracted. Such an artificial heart has a pump body comprising a cylindrical axial-flow pump section, a nozzle section provided on its distal end and a driving section provided on the proximal end of the axial-flow pump section. The cardiac apex of a ventricle of a human heart is cut and a short cylindrical cardiac apex ring is embedded therein. The pump section and the nozzle section are inserted in the ventricle through the cardiac apex ring, and the distal end of the nozzle section is inserted in an aorta through its aorta valve or the like. The driving section which has a large volume is embedded in a portion of the thorax which is outside of the human heart.

The artificial hearts has the following problem in connection with the function of a shaft-sealing mechanism provided between the pump section and the driving section. With the artificial heart, a motor and other elements are housed in the driving section, and the rotor of the pump section is driven via a driving shaft extending from the driving section to the pump section. Blood supplied by systemic blood pressure flows through the pump section. In this arrangement, blood is not allowed to enter the space in the driving section. If blood enters the space defined in the driving section, coagulation of blood occurs and the operation of the motor stops.

It is necessary to provide, between the driving section and the pump section, a sealing mechanism for sealing the driving shaft in a liquid tight state in order to prevent blood from entering the interior of the driving section. Since, however, the artificial heart is embedded in a human body, the artificial heart must be operated for a long time without maintenance. It is not easy with the present technology to provide a shaft-sealing mechanism with which perfect sealing is maintained for a long time.

### SUMMARY OF THE INVENTION

The object of this invention is to provide an artificial heart which has a shaft-sealing mechanism for completely preventing blood from entering the interior of a driving section for a long time.

An auxiliary artificial heart according to this invention inserted in a ventricle of a human heart, including a cylindrical cardiac apex ring embedded in the cardiac apex of the human heart by cutting the cardiac apex, and a main body of the artificial heart comprising a cylindrical axial flow pump section inserted in the ventricle of the human heart through the cardiac apex ring, a nozzle section extending outward from the distal end of the pump section through the aorta valve of the human heart and a driving section provided on the proximal end of the pump section and disposed outside (or externally) of the human heart, for driving the pump section through a driving shaft.

Between the driving section and the pump section is provided a sealing mechanism for maintaining the driving shaft in a liquid tight state to prevent blood from entering the interior of the driving section from the pump section. The sealing mechanism defines a sealing liquid chamber surrounding the driving shaft at the driving section and a sealing liquid is filled in the sealing liquid chamber.

According to a preferred embodiment, the sealing liquid includes a physiological sodium chloride solution or an anticoagulant such as heparin, and the sealing liquid chamber communicates with a sealing liquid bag made of flexible material, filled with the sealing liquid and embedded in the human body.

The sealing mechanism is provided with an oil seal made of elastic material, closely fitted on the outer peripheral surface of the driving shaft due to its elastic deformation and forming a lubricating film of the sealing liquid between the peripheral surface of the driving shaft and the oil seal.

The pump section is driven by a motor or the like driving unit housed in the driving section. The pump section sucks blood from a ventricle of a human heart and discharges it into an aorta from the nozzle section of the distal end of the pump section by bypassing the aorta valve or the like. Thus, blood is delivered to the aorta not only by the beating of the human heart but also by means of the artificial heart. The artificial heart supplements any insufficient amount of blood which is not provided by the human heart, whereby it is ensured that the necessary amount of blood can be delivered. The volume of the pump section is smaller than the volume of the ventricle of the human heart when it contracts most so as not to interfere with natural beating of the human heart.

The sealing mechanism prevents blood from entering the driving section from the pump section. In this case, the sealing mechanism defines a sealing liquid chamber at the driving section, and a sealing liquid such as a physiological sodium chloride solution fills the sealing liquid chamber. Sealing and lubrication of the sealing mechanism are ensured by the sealing liquid, and blood is securely prevented from entering the interior of the driving section from the sealing mechanism.



Even if the sealing mechanism is deteriorated and blood enters the mechanism, the blood which has entered the mechanism is mixed with the sealing liquid. Thus, blood is not coagulated and does not prevent the smooth operation of the artificial heart.

In the embodiment, the sealing mechanism is provided with an oil seal which forms a lubricant film of the sealing liquid between the oil seal and the outer peripheral surface of the driving shaft and is elastically closely fitted on the outer peripheral surface of the driving shaft for securely preventing the entrance of blood such that the oil seal is not worn and is durable. The oil seal can be designed such that the lubricant film formed between the oil seal and the outer peripheral surface of the driving shaft delivers blood in only one direction toward the pump section. This structure prevents blood from entering the interior of the driving section.

According to the preferred embodiment, the sealing liquid chamber communicates with the sealing liquid bag embedded in the human thorax or other location. A sealing liquid is supplemented from the sealing liquid bag and thus can be supplied to the sealing liquid chamber for a long time.

In a preferred embodiment, the driving shaft uses a dynamic pressure bearing made of ceramic material operated in the sealing liquid. A coating film is formed between the sliding surfaces due to the dynamic pressure of the sealing liquid, thereby reducing rotational resistance of the bearing and preventing wear, leading to high reliability.

When the driving shaft is rotated, the dynamic pressure bearing generates dynamic pressure. The dynamic pressure provide a liquid seal between the sealing liquid chamber and the driving section. The sealing liquid is thereby prevented from flowing from the sealing liquid chamber into the driving section.

The dynamic pressure bearing, which is mounted on the distal end portion of the driving shaft, supplies the sealing liquid to the oil seal. Hence, the sealing liquid circulates in the artificial heart, preventing foreign bodies from depositing.

In a further preferred embodiment, a metal plating is formed on the outer peripheral surface of the driving shaft. Tetrafluoroethylene and its derivatives are made eutectic in the metal plating film, thereby improving not only lubricating properties between the driving shaft and the oil seal but also durability.

The metal plating film of this kind is water-repellent and is well compatible with the living body. Any component that contacts blood or other body fluid may be covered entirely with such a metal plating film.

Additional objects and advantages of the invention will be set forth in the description which follows, and in part will be obvious from the description, or may be learned by practice of the invention. The objects and advantages of the invention may be realized and obtained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate presently preferred embodiments of the invention, and together with the general description given above and the detailed description of the preferred embodiments given below, serve to explain the principles of the invention.

FIG. 1 is a cross-sectional view of an artificial heart of a first embodiment of this invention, provided in the left ventricle of a human heart;

FIG. 2 is a longitudinal cross-sectional view of the main body of the artificial heart of the first embodiment;

FIG. 3 is a cross-sectional view of a sealing section;

FIG. 4 is an enlarged cross-sectional view showing the structure of a film formed on the outer peripheral surface of a driving shaft;

FIG. 5 is an exploded view of one of two dynamic pressure bearings;

FIG. 6 is an exploded perspective view of the other dynamic pressure bearing;

FIG. 7 is a diagram showing the dynamic pressure bearing, as viewed in the direction of arrows 7 in FIG. 5;

FIG. 8 is a diagram showing the dynamic pressure bearing, as viewed in the direction of arrows 8 in FIG. 5;

FIG. 9 is a sectional view taken along line 9 in FIG. 8;

FIG. 10 is a longitudinal cross-sectional view of another embodiment of the dynamic bearing;

FIG. 11 is a longitudinal cross-sectional view of a further embodiment of the dynamic bearing;

FIG. 12 is a longitudinal cross-sectional view of the main body of an artificial heart of a second embodiment according to this invention;

FIG. 13 is a longitudinal cross-sectional view of the main body of the artificial heart of a third embodiment according to this invention;

FIG. 14 is an enlarged longitudinal cross-sectional view of part of FIG. 13;

FIG. 15 is a longitudinal cross-sectional view of the main body of an artificial heart according to a further embodiment of the present invention;

FIG. 16 is a cross-sectional view illustrating the bearing tube, seat ring and follow ring forming part of a sealing mechanism for the embodiment of FIG. 15;

FIG. 17 is an elevational view of the drive shaft and bearings therefor;

FIG. 18 is a longitudinal cross-sectional view of a main body of an artificial heart according to a still further embodiment hereof;

FIG. 19 is a fragmentary longitudinal cross-sectional view of the sealing mechanism of the embodiment illustrated in FIG. 18; and

FIG. 20 is a view similar to FIG. 19 illustrating a further form of sealing mechanism.

FIG. 21 shows the state of an artificial heart having a centrifugal pump embedded in a body cavity;

FIG. 22 is a longitudinal cross-sectional view of the main body of the artificial heart of a seventh embodiment;

FIG. 23 is a longitudinal cross-sectional view of the main body of the artificial heart of an eighth embodiment;

FIG. 24 is a longitudinal cross-sectional view of the mechanism of a ninth embodiment;

FIG. 25 is a longitudinal cross-sectional view of the mechanism of a tenth embodiment; a longitudinal cross-sectional view of the

FIG. 26 is a longitudinal cross-sectional view of the mechanical seal mechanism of an eleventh embodiment;

FIG. 27 is a longitudinal cross-sectional view of the mechanical seal mechanism of a twelfth embodiment;

FIG. 28 is a longitudinal cross-sectional view of the main body of the artificial heart of a thirteenth embodiment; and

FIG. 29 is a longitudinal cross-sectional view of the mechanical seal mechanism of a fourteenth embodiment.



DETAILED DESCRIPTION OF THE  
PREFERRED EMBODIMENTS

The embodiments of this invention will be described with reference to the accompanying drawings.

A first embodiment of this invention is shown in FIGS. 1 to 6. FIG. 1 shows an artificial heart of this invention embedded in the left ventricle B of the heart A of a patient (hereinafter referred to as the "human heart"). A cardiac apex, a left atrium, a mitral valve, an aorta valve and an aorta are designated by C, D, E, F and G, respectively.

The artificial heart 1 comprises a cardiac valve ring 2 and the main body 3 of the artificial heart. The cardiac valve ring 2 is a short cylindrical member having a flange and is embedded in the human heart A through the cardiac apex C of the human heart A after the cardiac apex C has been cut. The main body 3 of the artificial heart 1 comprises a pump section 4, a nozzle section 6 provided on the distal end of the pump section 4 and a driving section 5 provided on the proximal end of the pump section 4. The pump section 4 and the nozzle section 6 are inserted in the left ventricle B through the cardiac apex ring 2, and the nozzle section 6 is further inserted in the aorta G through the central portion of the aorta valve F. Liquid tightness is ensured between the cardiac apex ring 2 and the main body 3 by means of a sealing mechanism, for example, a sealing member 8.

The pump section 4 is a relatively small cylindrical member and it has a smaller volume than the volume of the left ventricle B when it contracts most so as not to prevent natural beats of the human heart A. In the pump section 4 is housed a small axial-flow pump which is driven by a motor provided in the driving section 5. The pump section 4 sucks blood from the left ventricle B at a suction port 7 formed in the outer peripheral surface of the section 4 and discharges the blood from the distal end of the nozzle section 6 into the aorta G with the aorta valve F bypassed.

The nozzle section 6 passing through the central portion of the aorta valve F is made of soft synthetic resin material that does not suppress the function of the aorta valve F and it does not injure the aorta valve F.

The driving section 5 is embedded in a portion of the thorax outside of the human heart A. In the driving section 5 are provided a motor and other elements such as electric cells and electronic control elements if they are required. The driving section 5 is connected by means of electric wires 9 to a non-contact type electrode 10 embedded in a portion of the human body close to the patient's skin H. A necessary electric power is supplied from an external electric source (not shown) to the driving section 5 through the electrode 10.

The driving section 5 is further connected to a sealing liquid bag 12 by a flexible tube 11. The sealing liquid bag 12 is made of flexible material and filled with a sealing liquid such as a physiological sodium chloride solution. The sealing liquid bag 12 is embedded in a suitable portion of the body of the patient, such as the thorax or the abdominal cavity.

The structure of the main body 3 will be described with reference to FIG. 2. The pump section 4 has a cylindrical casing 21 which is reduced in diameter at its distal end portion to form the nozzle section 6 and is connected at its proximal end portion to the driving section 5 by an extension 24. In the casing 21 are provided an axial-flow pump such as a propeller 22 and a plurality of guide vanes 23 for directing the blood flow. The suction port 7 is formed in the outer peripheral surface of the casing 21. In the casing 21 is

formed a continuous blood passage extending from the suction port 7 to the nozzle section 6 via the propeller 22 and the guide vanes 23. A thin cylindrical nozzle tube 25 made of flexible synthetic resin material is mounted on the nozzle section 6. As described above, the nozzle tube 25 is designed to improve the contacting properties of the nozzle tube 25 with the ventricle valve F, prevent injury of the ventricle valve F and prevent suppression of the function of the ventricle valve F. The nozzle tube 25 is a flexible thin cylindrical member. Thus, when the artificial heart happens to be out of order, the nozzle tube 25 is collapsed by the blood pressure in the aorta G so as to act as a check valve for preventing blood from flowing backward from the aorta G to the left ventricle B.

The distal end portion of the driving shaft 26 is connected to the propeller 22. The driving shaft 26 passes through the extension 24 and extends to the interior of the driving section 5. In the driving section 5 is provided a motor having a stator coil 32 and a rotor 33. The proximal end portion of the driving shaft 26 is connected to the rotor 33. A cover 34 seals the driving section 5 hermetically.

In this embodiment, the blood flow passage in the pump section 4 is made smooth. The center portion of the pump section 4 has a boss portion 61, in which the driving shaft 26 and the bearing 28 are inserted. The sealing mechanism 31 is located in the distal end of the boss section 61, and has a conical oil seal. The oil seal is fitted in the conical depression formed in the rear end of a propeller boss 63 of the propeller 22, with a small gap formed between the oil seal and the conical depression. The guide vane 23 has a boss 64 which opposes the front end of the propeller boss 63 and is located a short distance therefrom. No steps are made between the inner peripheral surface of the casing 21 and the outer surfaces of the boss section 61, propeller boss 63 and boss 64. A smooth annular blood flow passage is therefore formed between the inner peripheral surface of the casing 21 and the outer surfaces of the components 61, 63 and 64.

The suction port 7 is formed in the proximal part of the boss section 61. A plurality of flow regulating vanes 62 are arranged between the suction port 7 and the propeller 22.

Since the blood flow passage is smooth as described above, the blood can flow smoothly, enhancing the pump's efficiency and reducing the number of places where the blood does not flow. Hence, the possibility of thrombi is decreased.

The distal end portion of the driving shaft 26 is supported by a bearing 28 made of ceramic material, and the proximal end portion of the driving shaft 26 is supported by dynamic pressure bearings 35 and 36 made of ceramic material in the driving section 5. On the distal end portion of the driving shaft 26 is provided a sealing mechanism 31 for performing sealing between the interior of the pump section 4 and the interior of the driving section 5 such that blood in the pump section 4 is prevented from entering the driving section 5.

In the portion of the main body 3 between the sealing mechanism 31 and the driving section 31 (for example, the extension 24 of the casing 21) is formed a sealing liquid chamber 30 surrounding the driving shaft 26. A sealing liquid such as a physiological sodium chloride solution is filled in the sealing liquid chamber 30. If necessary, a blood coagulant such as heparin or any other chemical agents, if required are added to the sodium chloride solution.

The sealing liquid is not limited to physiological chloride solution. Heparin solution may be used as sealing liquid.

An axial groove 37 is formed between the outer wall 38 and dynamic pressure bearing. The space is filled with the



sealing liquid and substantially forms part of the sealing liquid chamber 30. Between the outer peripheral surface of the dynamic pressure bearing 35 and the inner peripheral surface of the casing 31 is formed an axial groove 37 which communicates with the sealing liquid chamber 30 and a narrow passage 38 formed in the inside wall of the driving section 5. The sealing liquid chamber 30 communicates with the sealing liquid bag 12 via the groove 37, the passage 38 and the tube 11.

The sealing mechanism 31 will be described. In this embodiment, an oil seal is used as the oil seal 31. The oil seal is made of elastic material such as synthetic rubber, and has an elastically deformable lip portion which abuts against the outer peripheral surface of the driving shaft 26 to maintain liquid tightness. The oil seal has a specific feature in that a lubricating film of the sealing liquid is formed between the oil seal itself and the drive shaft 26. This lubricating film ensures sealing and prevents direct contact of the oil seal with the outer peripheral surface of the driving shaft 26 such that the oil seal is free from wear for a long time.

In FIG. 3 is shown an preferred embodiment of the seal mechanism 31 provided with an oil seal 41 made of synthetic rubber, for example, and having a elastically deformable lip portion 42. The inner peripheral surface of the lip portion 42 is in contact with the outer peripheral surface of the driving shaft 26. A garter spring 43 is provided on the oil seal, for stabilizing contact pressure between the lip portion 42 and the outer peripheral surface of the driving shaft 26. As described above, the oil seal 42 is designed such that a thin lubricating film of the sealing liquid is formed between the inner peripheral surface of the lip portion 42 and the outer peripheral surface of the driving shaft 26. The sealing liquid acting as the lubricating film is adapted to circulate on the sealing surface by the rotation of the driving shaft 26.

Further, in this embodiment, the sealing liquid acting as the lubricating film is adapted to flow in only one direction toward the pump section 4 so that the sealing liquid flows little by little through the pump section 4. This behavior of the sealing liquid securely prevents blood from entering, from the pump section 4, the sealing surface defined between the oil seal 41 and the driving shaft 26.

Since the sealing liquid is a sodium chloride solution and a very small amount of the solution flows into the pump section 4, it does not affect the human body. It is sufficient that the amount of the flowing-out sealing liquid is several cubic centimeters per month, for example, and the amount of the sealing liquid corresponding to the discharged amount is supplied from the sealing liquid bag 12. When, therefore, several to ten cubic centimeters of the sealing liquid is contained in the sealing liquid bag 12, it is unnecessary to supplement the sealing liquid for more than a year.

The oil seal 41 may be made of various materials. Examples of the materials are: silicone rubber, urethane rubber, ethylene-propylene rubber, nitrile rubber, fluororubber, acrylic rubber, natural rubber, fluororesin, polytetrafluoroethylene, polyurethane, and the like.

A coating is formed on the outer peripheral surface of the driving shaft 26 in order to improve lubricating properties between the oil seal 41 and the driving shaft 26 and enhancing durability. The coating will be described with reference to FIG. 4.

The oil seal 41 is elastically closely fitted on the outer peripheral surface of the driving shaft 26 to prevent blood entrance. Surface treatment is required on the driving shaft 26 so as to maintain the sealing function of the oil seal 41 for a long time. This is because the driving shaft 26 also

needs to have good lubricating properties, wear-resistance, and durability. In this embodiment, a compound plating film 52 is formed on the surface of the driving shaft 26. The compound plating film 52 is formed by making a great number of tetrafluoroethylene fine particles 51 distributed evenly in an electroless nickel plating film so as to be eutectic. In the embodiment, the eutectic amount of tetrafluoroethylene is about 25%.

The driving shaft 26 is made of stainless steel, for example. After cleaning (or removing oily material) and activating, nickel is flush-plated on the driving shaft 26. Thereafter, a nickel-plated film having a thickness of several micrometers is formed in a nickel-phosphorus plating solution in which there are distributed tetrafluoroethylene fine particles which have been made hydrophilic by a surface active agent. By this treatment, fine particles 57 of tetrafluoroethylene are made eutectic in the nickel plating film, and a compound plating film 58 is formed as shown in FIG. 4.

When the base material of the driving shaft 26 is hardened by heat treatment, the compound plating film 52 provides Vickers hardness of 500 to 600. Since fine particles 57 of tetrafluoroethylene are exposed on the surface of the compound plating film 58, they provide good lubricating properties and water-repellent properties. Fine particles 57 of tetrafluoroethylene is suited for human bodies well. The fine particles 57 are held in the nickel plating film and are combined together. Thus, the fine particles 57 are held firmly so as not to fall off the plating film.

The compound plating film 58 is water-repellent, prevents coagulation of blood, and is compatible with the living body. The film 58 may be formed not only on the outer peripheral surface of the driving shaft 26 which contacts the oil seal 41, but also on the other components of the artificial heart which contact blood and/or other body fluids.

The sealing mechanism 31 is not limited to an oil seal but can be applicable to the other sealing mechanism such as a labyrinth packing, if the conditions allow.

A dynamic pressure bearing assembly will be described with reference to FIG. 5. The dynamic pressure bearing assembly rotatably supports the proximal end portion of the driving shaft 26 and performs sealing between the sealing liquid chamber 30 and the space in the driving section 5, as well.

The dynamic pressure bearing assembly comprises an outer fixed-side bearing 35 and an inner rotary-side bearing 36 which are made of ceramic material. The fixed-side bearing 35 and the rotary-side bearing 36 have cylindrical portions 35a and 36a and flange portions 35b and 36b, respectively. The cylindrical portion 36a of the rotary-side bearing 36 is closely fitted in the cylindrical portion 35a of the fixed-side bearing 35, and the flange portions 35a and 35b are in a close contact with each other.

A plurality of dynamic-pressure generating grooves 51 and 52 are formed in the outer peripheral surface of the cylindrical portion 36a of the rotary-side bearing 36 and the contacting surface of its flange portion 36b.

The abutting surface of the flange portion 35b of the fixed-side bearing 35 is flat as illustrated in FIG. 7. A plurality of dynamic-pressure generating grooves 52 are formed in the abutting surface of the flange portion 46b of the rotary-side bearing 36 as shown in FIG. 8. The grooves 52 are curved as shown in FIG. 8. They are shallow as illustrated in FIG. 9, about 3 to 10 microns deep. Those portions of the surface, or the lands 36c located among the grooves 52, and the surface of the flange portion 35b of the fixed-side bearing 35 is smooth, having undulation of 0.3



microns or less and maximum roughness of about 0.1 micron. The dynamic-pressure generating grooves **52** have been formed by shot blasting the abutting surface of the flange portion **46b**.

A pair of dynamic-pressure generating grooves **51** are formed in the outer peripheral surface of the cylindrical portion **36a** of the rotary-side bearing **36**. These grooves **51** are shaped like a herringbone and have the same depth as the dynamic-pressure generating grooves **52** formed in the abutting surface of the flange portion **46b**. The grooves **51** extend in the opposite directions. Hence, when the driving shaft **26** is rotated, they guide the sealing liquid in the opposite directions.

The operation of the dynamic pressure bearings **35** and **36** will be described.

When the driving shaft **25** is rotated, the rotary side bearing **36** is rotated, too. The sealing liquid is thereby supplied from the dynamic-pressure generating grooves **52** toward the center of the flange portion **36b**, guided along the dynamic-pressure generating grooves **51** formed in the abutting surface of the flange portion **36b**. The sealing liquid is simultaneously supplied to the middle portion of the cylindrical portion **36a**, also along the dynamic-pressure generating grooves **51**.

As a result, a layer of sealing liquid is formed under high pressure at the center of the flange portion **36b**. Located between the fixed-side bearing **35** and the rotary-side bearing **36**, the sealing liquid layer prevents a mechanical contact between the bearings **35** and **36**. It serves as lubricant, enabling the rotary-side bearing **36** to rotate with an extremely low resistance applied to it, and preventing wear of the bearing **36**. The cylindrical portion **36a** and flange portion **36b** of the rotary-side bearing **36** bear the radial load and thrust load exerted by the driving shaft **26**, respectively.

Since the dynamic-pressure generating grooves **51** and **52** guide the sealing liquid under high pressure to the center of the flange portion **36b** and the middle portion of the cylindrical portion **36a**, the liquid reliably serves as lubricant though the liquid itself has poor lubrication action.

Both the fixed-side bearing **35** and the rotary-side bearing **36** are made of a hard ceramic material such as sintered SiC, sintered  $\alpha$ -SiC containing BeO, or sintered  $\text{Si}_3\text{N}_4$ . The ceramic materials exemplified are very hard and have a small coefficient of friction. No wear occurs between the bearings **35** and **36** even if they directly contact each other when the motor is started or stopped or while the motor shaft is rotating.

In FIG. **6** is shown the bearing **28** which comprises a rotary-side bearing **28a** and a fixed-side bearing **28b**. A pair of dynamic-pressure grooves **70** similar to the dynamic-pressure grooves **51** are formed in the outer peripheral surface of the rotary-side bearing **28a**. By the paired dynamic-pressure grooves **70**, the sealing liquid is delivered in the opposite directions and a sealing liquid film is formed between the outer peripheral surface of the rotary-side bearing **28a** and the inner peripheral surface of the fixed-side bearing **28b**. The sealing liquid film reduces resistance of rotation, prevents wear and improves durability.

The bearing **28** may have a structure as shown in FIG. **10**. A plurality of dynamic-pressure generating grooves **71** are formed in the outer peripheral surface of the rotary-side bearing **28a**. Each of these grooves **71** consists of two herringbone-shaped grooves **71a** and **71b** which extend in different directions. The groove **71a** is longer than the groove **71b**. The dynamic pressure generated in the dynamic-pressure generating grooves **71** forms a sealing

liquid film between the rotary-side bearing **28a** and the fixed-side bearing **28b** and delivers the sealing liquid toward the oil seal **41**. The delivered sealing liquid leaks little by little from between the oil seal **41** and the driving shaft **26** so as to prevent blood from entering the driving section.

Therefore, the bearing **28** functions not only as a bearing but also as a micropump for supplying the sealing liquid to the oil seal in tiny amounts.

In FIG. **11** is shown another embodiment of the bearing **28** formed in its outer surface with a pair of groups of dynamic-pressure generating grooves and a series of dynamic-pressure generating grooves **75**. The paired groups of dynamic-pressure generating grooves **74** deliver sealing liquid in the opposite directions to form a sealing liquid film between the rotary-side bearing **28a** and the fixed-side bearing **28b**. The dynamic-pressure generating grooves **75** act to deliver the sealing liquid toward the oil seal **41**. The sealing liquid is supplied from the supply port **73** to the portion between the dynamic-pressure generating grooves **74** and **75**.

A second embodiment of this invention will be described with reference to FIG. **12**. The motor housed in the driving section **5** in this embodiment is of an immersed type in a liquid so as to circulate a sealing liquid.

The space in the driving section **5** in this embodiment is filled with the sealing liquid, and the stator **32** and the rotor **33** of the motor are immersed in the sealing liquid. In the proximal end portion of the driving section **5** is formed a passage **55** which is connected to a sealing liquid bag **12** via a pipe **56**. In this embodiment, the dynamic pressure bearings **35** and **36** do not perform sealing but act as pumps for supplying the sealing liquid in the driving section **5** toward the sealing liquid chamber **30**.

In this embodiment, the sealing liquid circulates by the pump action due to the dynamic pressure generated by the dynamic pressure bearings **35** and **36** in such a manner that the sealing liquid is supplied from the interior of the driving section **5** to the sealing liquid chamber **30** then to the sealing liquid bag **12** through the groove **37**, the passage **38** and the pipe **11** and returns to the interior of the driving section **5** through the pipe **56** and the passage **55**.

Since the interior of the driving section **5** of this embodiment is filled with the sealing liquid, motor resistance increases. However, it is unnecessary to consider damage if the sealing liquid enters the driving section **5** in this embodiment as it does in the first embodiment, leading to an easy design and enhancing reliability. Because of the circulation of the sealing liquid, the liquid carries heat generated in the stator coil **32** of the motor or the like to the sealing liquid bag such that the heat can be dissipated in the human body in a dispersed manner. Thus, the temperature of the sealing liquid and the driving section **5** is maintained substantially as high as the temperature of the human body. It is unnecessary, therefore, to consider the possibility of low-temperature damage even if the temperature of the surface of the driving section **5** rises more than the temperature of the human body. This makes the design consideration for heat radiation of artificial hearts simple and enhances its reliability. The other structures of the second embodiment are the same as those of the first embodiment. The parts and elements of the second embodiment which are the same as those of the first embodiment are designated by the same reference numerals and the description thereof is omitted.

A third embodiment of this invention is shown in FIGS. **13** and **14**. Similar to the second embodiment as shown in FIG. **12**, the artificial heart of this embodiment circulates a



sealing liquid through the main body of the artificial heart and a sealing liquid bag 12. The sealing liquid flows from the supplying port 55 formed in the rear end portion of the driving section 5 into the main body of the artificial heart and then flows out from the vicinity of the sealing mechanism 31 into the sealing liquid bag 12. In this way, the sealing liquid is circulated. In this embodiment, therefore, the sealing liquid circulates in the overall main body of the artificial heart, whereby the interior of the main body is always maintained clean, leading to high reliability.

A filter 80 is provided in the sealing liquid bag 12, for removing foreign matter contained in the sealing liquid returned from the main body of the artificial heart such that the sealing liquid is always clean. The sealing liquid bag 12 is provided with a liquid therapy port 81 through which the sealing liquid is supplemented or replaced.

FIG. 14 is an enlarged partial view of the sealing mechanism 31 of the main body of the artificial heart of this embodiment. A pair of groups of dynamic pressure grooves 82 and 83 are formed in the outer peripheral surface of the rotary-side bearing 28a of the bearing assembly 28. One group of dynamic pressure grooves 82 are longer in the axial direction than the other group of dynamic pressure grooves 83 such that the former group delivers more sealing liquid than the other group. With this structure, therefore, the sealing liquid is sent in opposite directions by the dynamic pressure grooves 82 and 83 and a sealing liquid film is formed between the rotary-side bearing 28a and the fixed-side bearing 28b due to dynamic pressures in the dynamic pressure grooves 82 and 83. Since the former group of dynamic pressure grooves 82 deliver more sealing liquid than the latter group of dynamic pressure grooves 83 do, the sealing liquid is supplied toward the oil seal 41.

When the sealing liquid which is being sent toward the oil seal 41 passes through the orifice portion 84, the flow speed of the liquid increases and is sent to a rear side portion of the oil seal 51. Vane projections 85 are formed on the portion of the driving shaft 26 which is close to the oil seal 41. As the driving shaft 26 rotates, the vane projections 85 agitate the sealing liquid therearound and deliver it to the rear side portion of the oil seal 41. As a result, neither the sealing water nor foreign matter stay in the rear side portion of the oil seal 41, whereby sealing of the oil seal 41 is securely maintained.

In the wall of the extension 24 of the casing 21 of the main body of the artificial heart is formed an exhaust passageway 81 through which the sealing liquid in the rear side portion of the oil seal 41 is sent to the sealing liquid bag 12.

In FIGS. 15 to 17, a fourth embodiment of the present invention is shown. In the fourth embodiment, mechanical seals are applied to the sealing mechanism of the driving shaft. While in the previous embodiment, oil seals are used for the sealing mechanism of the driving shaft, the fourth embodiment employs mechanical seals to enhance its durability.

The fourth embodiment is almost the same as the above described embodiment except for the sealing mechanism and its related portions. Specifically, in FIG. 15 numeral 105 indicates a driving section, and 104 denotes a pump section. As in the previous embodiment, the pump section 104 is inserted into the left ventricle B via a cardiac apex ring 2.

In the driving section 105, a motor 106 is provided. The motor 106 is a canned motor where a rotor is housed in a casing filled with liquid. Numeral 107 indicate a stator coil and 108 a rotor the spacing between the rotor 108 and the casing, or an air gap 109 is designed to allow a sealing liquid

such as used in the previous embodiment to circulate in the driving section 105, a sealing liquid inlet 110 and a sealing liquid outlet III are made. They are connected to a seal liquid bag 112 via flexible circulation tubes 1-14, 115, respectively. Then, the sealing liquid circulates between the sealing liquid bag 112 and the inside of the artificial heart. In the sealing liquid bag 112, there is provided a filter, which removes foreign matter mixed in the circulating sealing liquid.

The pump section 104 contains a thin-wall, cylindrical tube section 120 and a casing section 121 formed at the tip portion of the tube section. In the casing section 121, a pump rotor composed of a rotor boss 123 and a plurality of rotor blades 124 provided on the boss so as to project from around the boss is housed. The pump rotor is rotated by the motor 106. Numeral 128 indicates a spinner that provides flow straightening in the casing section 121; there are a plurality of stator vanes 125 and a plurality of front stator vanes also serving as a stay for the casing section 121.

On the base end side of the casing section 121, a fluid inlet 127 is made, through which the blood in the left ventricle of the heart is sucked. The blood is discharged from the distal end of a nozzle section 122. The nozzle section 122 is inserted in the aorta through the aorta valve of the heart.

The number of the stator vanes 125, 126 and that of rotor blades 124 are set at values that do not contain the common factors or integral multiples of the common factors, that is, at prime factors with respect to each other, which thereby prevents the resonance or pulsation of blood sent by rotation of the rotor blades 124.

Explained next will be the driving shaft of the artificial heart and its sealing mechanism in the present embodiment. In FIG. 15, numeral 130 indicates a driving shaft. The base end portion of the driving shaft 130 is connected to the rotor 108 of the motor 106. The tip end portion of the shaft is connected integrally to the rotor boss 123 of the pump rotor, which is driven via the driving shaft 130. In the tube section 120 of the pump section 104, a cylindrical bearing tube 131 is housed. The driving shaft 130 is inserted in the bearing tube 131.

At the tip portion of the bearing tube 131, a mechanical sealing mechanism 132 acting as a sealing mechanism is provided. The mechanical sealing mechanism 132 prevents the blood in the left ventricle of the heart from entering the inside the artificial heart.

The construction of the mechanical sealing mechanism 132 will be described with reference to FIGS. 15 to 17. At the tip portion of the bearing tube 131, a flange-like fixed-side seat ring 133 is formed. The end of the seat ring 133 is machined precisely so as to have a smooth surface perpendicular to the rotation axis of the driving shaft 130 and provides a sealing surface. A rotary-side follow ring 134 is in close contact with the sealing surface of the seat ring 133 so as to rotate freely, thereby maintaining the seal. The follow ring 134 has a disk shape and is provided integrally at the tip portion of the driving shaft 130 so as to be precisely perpendicular to the rotation axis of the driving shaft.

Furthermore, at the base end portion and tip portion of the driving shaft 130, bearing sections 135 and 136 are integrally formed, respectively. These bearing sections 135, 136 are cylindrical and supported by the inner surface of the bearing tube 131 so as to rotate freely. The outer surface of these bearing sections 135, 136 and the inner surface of the bearing tube 131 are machined precisely. These bearing sections 135, 136 and bearing tube 131 support the driving shaft 130 precisely so as to rotate freely.



As shown in FIG. 17, spiral shallow dynamic-pressure grooves **140** are made in the outer surface of these bearing sections **135**, **136**. These dynamic-pressure grooves **140**, when the driving shaft **130** rotates, introduces the sealing liquid into the spacing between the outer surface of these bearing sections **135**, **136** and the inner surface of the bearing tube **131**, thereby assuring lubrication between them, and allows the sealing liquid to flow toward the tip portion at a specific rate. Therefore, these bearing sections **135**, **136** and bearing tube **131** constitute a one-way dynamic-pressure bearing that functions as both a bearing for supporting the driving shaft **130** and a pump for feeding the sealing liquid. Furthermore, the driving shaft **130** is not restricted in the direction of the axis with respect to the bearing tube **131**, but can move freely in the axis direction. In the driving section **105**, a ring-shaped permanent magnet **146** is provided on the fixed-side of the housing of the driving section. A ring-shaped permanent magnet **146** is also provided on the rotor **108** of the motor **106**, that is, on the driving shaft **130** side. These permanent magnets **145**, **146** face each other with a specific distance between them. The polarity of these permanent magnets **145**, **146** is set so that they may repel one another in the axis direction. The repulsion of these permanent magnets **145**, **146** actuates the driving shaft **130** so that the shaft may move toward the base end, thus pressing the follow ring **134** on the driving shaft **130** against the seat ring **133**, thereby maintaining the sealing effect of the mechanical sealing mechanism **132**.

The spacing between the bearing tube **131** and the driving shaft **1-30** is designed to act as sealing liquid chambers **137**, **138** through which the sealing liquid circulates. The sealing liquid chamber **138** is isolated from the outside, that is, the blood passageway in the left ventricle of the heart, by the mechanical sealing mechanism **132**, thereby maintaining the seal.

In the outer portion of the tube section **120** of the pump section **104**, a circulation passage **142** is made. The tip portion of the circulation passage **142** is connected to the sealing liquid chamber **138** and its base end portion is connected to the sealing liquid outlet **111**. Therefore, the sealing liquid flows from the sealing liquid bag **112** through the circulation tube **114** and sealing liquid inlet **110** into the air gap **109** of the motor **106**. Then, by the pumping action of the one-way dynamic-pressure bearing composed of the bearing sections **135**, **136** and bearing tube **131**, the sealing liquid is sent, through the sealing liquid chambers **137**, **138** toward the back of the mechanical sealing mechanism **132** at a specific pressure. The sealing liquid fed to the sealing liquid chamber **138** is returned to the sealing liquid bag **112** via the circulation passage **142**, sealing liquid outlet **111**, circulation tube **115**, and filter **113**, and circulates in this route.

The function and advantage of the fourth embodiment described above are as follows. First, with the one-way dynamic-pressure bearings **135**, **136** feed the sealing liquid to the sealing liquid chamber **138** at a specific pressure. The sealing liquid forms a thin film of 0.5 to 1.0 mm in thickness between the seat ring **133** of the mechanical sealing mechanism **132** and the sealing surface of the follow ring **134**. The thin film effects lubrication and sealing between the seat ring and the follow ring. This prevents blood from entering the sealing liquid chamber **138**, or the inside of the artificial heart.

When the artificial heart is actually used, protein in the blood, but only a little may enter due to diffusion. This protein is coagulated by heating due to the sliding friction between the seat ring and follow ring that rotate relatively

with respect to each other. Particles of the coagulated protein are discharged outward under the influence of the centrifugal force of the follow ring **134** that is rotating, and are washed away by the blood flowing outside the mechanical sealing mechanism. The particles of the coagulated protein are so small that they have no adverse effect on the human body even if diffused into the blood.

Although the coagulated protein may adhere at the inner peripheral edge portions of the seat ring **133** and follow ring **134**, such protein particles will be washed away by the sealing liquid circulating inside the mechanical sealing mechanism **134**, or inside the sealing liquid chamber **138**. These protein particles are captured by the filter **113** in the sealing liquid bag **112**, so that the sealing liquid will not be contaminated.

The fourth embodiment using the mechanical sealing mechanism as the sealing mechanism has the following advantages, as compared with the previous embodiment using an oil seal as the sealing mechanism.

Although an oil seal has a simple structure and keeps well in close contact with the driving shaft, when protein in the blood diffuses between the oil seal and the peripheral surface of the driving shaft and coagulates there, the coagulated protein will not be discharged by centrifugal force as described above because the oil seal is in contact with the peripheral surface of the driving shaft. Furthermore, since the oil seal is highly flexible, when coagulated protein deposits between the peripheral surface of the driving shaft and the oil seal, the internal diameter of the oil seal extends easily, increasing the spacing between the peripheral surface of the driving shaft and the oil seal. This increase in the spacing increases the flow rate of the sealing liquid flowing outside through the spacing. The flow of the sealing liquid washes away the coagulated protein into the blood, resulting in an increase in the amount of sealing liquid flowing outside, or the consumption of the sealing liquid. Because of this it is necessary to frequently supply additional sealing liquid to the sealing liquid bag, imposing a heavier burden on the patient.

In contrast, with the mechanical sealing mechanism, centrifugal force discharges the coagulated protein as described earlier, so that the spacing between the seat ring and the follow ring is constantly kept narrow. As a result, the volume of sealing liquid flowing outside is smaller and consequently the frequency of adding the sealing liquid is lower, easing the burden on the patient.

In addition, the sealing liquid circulated as described above cools the mechanical sealing mechanism **132**, effectively preventing part of the mechanism from being locally heated to high temperatures due to sliding friction. This prevents the blood cells from being destroyed as a result of the blood touching high-temperature portions.

In addition, a mechanical seal is more durable than the oil seal, because the seat ring and follow ring are made of ceramic material or metal material.

In the above embodiment, the bearing tube **131** and driving shaft **130** defining the mechanical sealing mechanism are preferably formed of fine ceramic material, and the follow ring **134** is formed of graphite material. They are precision ground. The ceramic material is chemically stable and superior in dimensional stability. In the present embodiment, the bearing tube **131** and the seat ring **133** as well as the driving shaft **130** and the bearing sections **135**, **136** are formed integrally, so that the dimensional accuracy of their assembly and the resulting mechanical sealing mechanism are high. Consequently, the accuracy of the



positional relationship, such as the perpendicularity or concentricity of the seat ring **133** and follow ring **134** with respect to the rotation axis, is high, assuring a high reliability. Since the follow ring **134** is formed of carbon graphite, it matches the seat ring **133** well. Additionally, the graphite, a form of carbon, has self-lubricating properties, and the coefficient of friction is low.

The materials for these members are not restricted to what have been described above, but may be suitable combinations of various types of materials such as ceramic, graphite, composite materials, metal materials, and the like.

In the present embodiment, the follow ring **134** is pressed against the seat ring **133** in the mechanical sealing mechanism **132** by magnetic repulsion of the permanent magnets **145**, **146**, resulting in a simpler configuration and higher reliability. The urging pressure may come from attraction between the permanent magnets.

FIGS. **18** and **19** show a fifth embodiment of the present invention. The fifth embodiment is the same as the fourth embodiment except for part of the mechanical sealing mechanism and part of the circulation route of the sealing liquid.

Specifically, in the fifth embodiment, a driving shaft **230** and bearing members **235**, **236** are formed into separate members. The bearing member **235** on the base end side is supported by a bearing sleeve **240**, and the bearing member **236** on the tip end side is supported by a short bearing tube **231**. On the bearing member **235** on the base end side, a flange section **243** is formed, thereby constituting a thrust bearing.

Between the outer surface of the bearing sleeve **240** and the housing of the driving section **5**, a passageway **241** is formed. A passageway **242** is also formed between the inner surface of the bearing section **236** on the tip end side and the driving shaft **230**. The sealing liquid passes through these passageways and circulates through the sealing liquid chambers **137**, **138**. In the present embodiment, a sealing liquid circulating pump **250** is provided. Outside the body or inside the abdominal cavity of the patient, and the pump **250** circulates the sealing liquid.

At the tip end portion of the bearing tube **231**, is an integrally formed flange-like seat ring **133**. The follow ring **134** is in close contact with the sealing surface of the end of the seat ring **133**. The follow ring **134** is a member separate from the driving shaft **230**. The follow ring **134** is installed on the rotor boss **223** of the pump rotor. The rotor boss **223** is designed to move freely a specific distance in the axis direction with respect to the driving shaft **230**. The follow ring **134** can move to some extent in the axis and the diameter direction with respect to the driving shaft **230**. An O ring provides sealing between the follow ring **134** and the driving shaft **230**.

The rotor boss **223** is hollow and houses a pair of disk-shaped permanent magnets **263**, **264** in it. One permanent magnet **263** is mounted on the rotor boss **223** and the other permanent magnet **264** is mounted on the driving shaft **230**. The polarity of these permanent magnets **263**, **264** is set so that they may repel each other. The force of repulsion presses the follow ring **134** against the end of the seat ring **133**.

In the present embodiment, the driving shaft **230**, rotor boss **233**, and follow ring **134** can move independently from each other. A relative movement between them can absorb vibrations caused by their rotation. This enables the follow ring **134** to be pressed against the end of the seat ring **133** more stably, resulting in an increase in the reliability of the mechanical sealing mechanism **132**.

In this embodiment, because the sealing liquid is circulated by the sealing liquid circulating pump **250**, the circulating flow rate and pressure of the sealing liquid can be regulated freely.

FIG. **20** shows a sixth embodiment of the present embodiment. In the sixth embodiment, the follow ring **134** is pressed against the seat ring **133** by a compression coil spring **270** in place of the pair of permanent magnets **263**, **264** in the fifth embodiment. The sixth embodiment has the same configuration as that of the fifth embodiment except as stated above. In FIG. **20**, the parts corresponding to those in the fifth embodiment are indicated by the same reference symbols and explanation of them will not be given.

The present invention can be applied to an artificial heart having a centrifugal pump. Hereinbelow, we will explain embodiments of an artificial heart comprising a pump section consisting of a centrifugal pump and a mechanical seal mechanism.

FIG. **21** shows the state of an artificial heart having a centrifugal pump embedded in a body cavity. To describe more specifically, the main body **303** of the artificial heart is constituted of a pump section **304** consisting of a centrifugal pump and a driving section **305** accommodating a motor therein. The main body **303** is embedded in the body cavity and on the outside of the heart.

Onto the pump section **304**, an entrance nozzle **327** is provided. To cardiac apex C of heart A, a cardiac apex ring **302** is fitted. The entrance nozzle **327** is inserted into a left heart ventricle B by way of the cardiac apex ring **302**.

To an exit nozzle **322** of the pump section **304** is connected an artificial blood vessel **360**, which is connected to aorta G without passing through the left ventricle B. The artificial vessel **360** is connected to aorta G by suture.

To the main body **303** is connected a supply tube **361**, which is guided out of the body cavity via appropriate means. In the supply tube **361** are accommodated a tube for circulating a sealing liquid and an electric wire for driving a driving section **305**. The sealing liquid is circulated by way of the main body **303** by a sealing liquid supply unit (not shown). Power is supplied to the driving section from an outside electric source via the electric wire.

In the artificial heart having the aforementioned structure, the blood of the left ventricular B is first sucked by the pump section **304** by way of the entrance nozzle **327**, pressurized by the pump section **304**, passed through the artificial blood vessel **360** via the exit nozzle **322**, and fed into aorta G without passing through the left ventricular B and a mitral valve. The artificial heart serves for supplying blood to aorta G without disturbing the natural heart beat in order to make up for shortage in blood supplied only by the natural heart beat.

FIG. **22** shows a main body **303** of the artificial heart having a centrifuge pump according to a seventh embodiment, shown in FIG. **21**. The main body **303** is constituted of the pump section **304** consisting of a centrifugal pump and a driving section **305**. In the pump section **304**, an impeller **324** is provided. A reference numeral **328** indicates a spinner. To the pump section **304** is provided an entrance port **326**, to which the entrance nozzle **327** is further provided. The pump section includes an exit port **322**, to which an end portion of the artificial vessel **360** is connected.

The driving section **305** houses a motor **306** having an driving shaft **330**. The top end portion of the driving shaft **330** is inserted into the pump section **304**, thereby being connected to the impeller **324**. Reference numerals **307**, **308**,



and **309** are a stator, rotor, and electric wire for supplying power to the motor, respectively.

In the driving portion **305** are disposed a sealing liquid inlet **310** and a sealing liquid outlet **311**, by way of which the sealing liquid is circulated through the driving section **305**.

To the portion in which the driving shaft **330** is just inserted into the pump section **304** is provided a mechanical seal mechanism **332**, which prevents blood passing through the pump section **304** from entering into the driving section **305**. To the casing side of the driving section **305** and to the rotor-side of the motor **306**, a pair of permanent magnets **345** and **346** are respectively provided so as to be opposed to each other. Attractive force generated between permanent magnets **345** and **346** is loaded on the driving shaft **330** in the lengthwise direction thereof, and consequently the force is added onto a portion between a seat ring and a follow ring of the mechanical seal mechanism **332** in the lengthwise direction, maintaining sealing between these rings. The sealing liquid is circulated through the mechanical seal mechanism **332** to ensure a sealing tightness and simultaneously to cool the mechanical seal mechanism **332**.

FIG. **23** shows the main body **303** of the artificial heart of an eighth embodiment of the present invention. The main body of this embodiment has substantially the same structure as that of the seventh embodiment of the present invention except that permanent magnets **345** and **346** are arranged so as to provide load to the driving shaft **330** in the lengthwise direction by repulsion force thereof. To avoid repetitions in FIG. **23**, like reference numerals designate like structural elements explained in FIG. **22** showing the seventh embodiment.

FIG. **24** shows the mechanical seal mechanism **332** of a ninth embodiment for use in the artificial hearts having a centrifugal pump of the seventh and eighth embodiments. The mechanical seal mechanism **332** is characterized in that a follow ring **334** of a flange form is provided onto the top of a driving shaft **360** and in that a cylindrical shaft bearing section **335** is formed so as to be integrated with the follow ring **334**. Furthermore, the periphery of the integrated structure is covered with a cylindrical seat ring **333**, which is provided to the casing of the driving section **305** and the like. The upper surface of the seat ring **333** is tightly connected to the lower surface of the follow ring **334**, thereby constructing the mechanical seal mechanism. The inner periphery of the seat ring **333** supports the seat bearing section **335** in such a way that the section **335** can be rotated freely. In this way, the seat bearing mechanism is constructed.

Between the seat ring **333** and the shaft bearing section **335** is formed a sealing liquid passage **370** of a ring-form. On the lateral side of the seat ring **333** is formed a sealing liquid flow-in port **371**. On the opposite side of the flow-in port **371** is formed a sealing liquid flow-out port **372**.

In the mechanical seal mechanism of the embodiment **8**, the seat ring **333** is made of a ceramic material. On the other hand, the follow ring **334** and the shaft bearing section **335** are made of a carbon composite material.

The sealing liquid circulating through the driving section **305** is supplied from the sealing liquid flow-in port **371** into the sealing liquid passage **370**, flows through the passage **370**, and goes out from the sealing liquid flow-out port **372**. The flow of the sealing liquid ensures the sealing tightness between the seat ring **333** and the follow ring **334**, thus preventing blood of the pump section **304** from flowing into the driving section **305**. On the other hand, the flow of the sealing liquid cools the seat ring **333** and the follow ring **334**, thus preventing temperature elevation taken place in the

sealing portion. Successful suppression of temperature elevation makes it possible to prevent coagulation of blood proteins taken place in a narrow interspace of the sealing portion. As a result, the sealing tightness is ensured and the seat ring **333** is prevented from adhering to the follow ring **334**.

To prevent coagulation of blood proteins as mentioned above, it is effective to reduce the temperature of a lubricating thin film of the sealing liquid to 50° C. or less which is present between the seat ring **333** and the follow ring **334**. This is because if the temperature of the lubricant thin film is suppressed to 50° C., or less, the coagulation of blood components in the space between the seat ring **333** and the follow ring **334** can be securely prevented since the most coagulation-susceptible component of the blood, namely, fibrinogen, is denatured by heat of about 50° C.

The temperature can be reduced by controlling the flow amount of the sealing liquid flowing through the sealing liquid passage **370**. If an excessive amount of the sealing liquid is used, the sealing liquid passing through the sealing portion and flowing into the pump section **304** is increased in amount. As a result, the sealing liquid will be consumed in a large amount and should be supplied more frequently. This result is not preferable since a patient receives a great burden. For the reasons mentioned above, it is important to set the flow amount of the sealing liquid at a minimum and sufficient amount required for controlling the temperature of the lubricating thin film to 50° C.—or less.

In practice, it may be preferred to perform a test using an artificial heart and determine the minimum and sufficient amount of the sealing liquid based on the experimental results obtained in the test. Since the artificial heart is embedded in a body when used, the peripheral temperature of the artificial heart is equal to the body temperature. It will be therefore easy to determine the minimum and sufficient flow amount to be needed if the experiment can be carried out under temperature as constant as the body temperature.

If the sealing portion between the seat ring **333** and the follow ring **334** can be further cooled by a different method other than the aforementioned cooling method employing a sealing liquid, the minimum and necessary flow amount can be set to a further smaller value. For example, it is effective to increase surface area to be exposed to the sealing liquid or blood by making the sealing surface in the form of flange. Alternatively, the following method is effective. The spinner **328** is formed solid by using highly heat conductive metal material and brought into contact with the upper surface of the follow ring **334**. If the spinner **328** thus constructed is used, heat can be released into blood through the spinner **328** by means of heat conduction.

There are various preferable embodiments of mechanical seal mechanism **332** other than those introduced in the above. In a tenth embodiment of the mechanical seal mechanism **332** shown in FIG. **25**, a follow ring **334** is formed independently of the shaft bearing section **335**. The sealing liquid passage **373** surrounding the driving shaft **360** is formed therebetween. The follow ring **334** may be formed of a material different from that forming the shaft bearing section **335**. For example, the follow ring **334** is formed of a carbon composite material to impart lubricity and to ensure sealing tightness; on the other hand, the shaft bearing section **335** is formed of a ceramic material to improve durability. The tenth embodiment has the same structure as that of the ninth embodiment shown in FIG. **9** except for the aforementioned respects. To avoid repetitions in FIG. **25**, like reference numerals designate like structural elements explained in FIG. **24** showing the ninth embodiment.



In an eleventh embodiment of the mechanical seal mechanism **332** shown in FIG. **26**, between a follow ring **334** and a spinner **32** is interposed a bumping material **373** formed of elastic material, e.g., ethylene propylene diene monomer (EPDM). The follow ring **334** is capable of moving in the lengthwise direction and diameter direction of a driving shaft **360**. By virtue of this structure, if the driving shaft **360** is vibrated, the vibration will be adsorbed by the bumping material **373**, preventing the vibration of transmitting to the follow ring **373**. In this mechanism, the follow ring **334** can be connected tightly and securely to a seat ring **333**, ensuring sealing tightness.

In the eleventh embodiment, a sealing-liquid introducing passage **374** is formed in the center portion of the driving shaft **360** along the lengthwise direction. The sealing-liquid introducing passage **374** is opened in the periphery surface to communicate with a sealing liquid passage **370**. The sealing liquid therefore blows out from the opening of the sealing liquid introducing passage **374**, and impinges upon the sealing portion of the follow ring **334** and the seat ring **333**. On the other hand, the sealing liquid is turned around in the sealing liquid passage **374** when a rotation shaft **360** is rotated. By virtue of these structural features, the sealing portion can be efficiently cooled.

The eleventh embodiment has the same structure as that of the tenth embodiment except for the aforementioned respects. To avoid repetitions in FIG. **26**, like reference numerals designate like structural elements explained in FIG. **25** showing the tenth embodiment.

In the twelfth embodiment of the mechanical seal mechanism shown in FIG. **27**, a head section **375** is provided onto the top of a driving section **360**. A bumping material **373** is interposed between the head section **375** and a follow ring **334**. The twelfth embodiment has the same structure as that of the eleventh embodiment except for the aforementioned respects. To avoid repetitions in FIG. **27**, like reference numerals designate like structural elements explained in FIG. **26** showing the eleventh embodiment.

The mechanical seal mechanisms according to the ninth to twelfth embodiments respectively shown in FIGS. **24** to **27** are suitable for the sealing mechanism for an artificial heart having a centrifugal pumps as described in the seventh and eighth embodiments shown in FIGS. **22** and **23**. Furthermore, application of these mechanical seal mechanisms may not be limited to the artificial heart having a centrifugal pump. The mechanical seal mechanisms may be, of course, applied to an artificial heart having an axial-flow pump as shown in FIG. **15** or **18**.

In a thirteenth embodiment of the artificial heart having a centrifugal pump, shown in FIG. **28**, a pump section **304** is formed so as to be integrated with an introducing nozzle **427** for introducing blood. The introducing nozzle **427** is bent along the shape of the left ventricle.

FIG. **29** shows the structure of a fourteenth embodiment of the mechanical seal mechanism **332** suitable for use in the artificial heart according to the thirteenth embodiment shown in FIG. **28**. The fourteenth embodiment employs a bumping material **373** having a cross-section of an inverted U-letter form. The bumping material **373** covers an outer peripheral surface, upper surface and inner peripheral surface of a follow ring **334**. Since bumping effect can be improved by the bumping material thus arranged, it is possible to reduce the bumping material **373** in thickness. Consequently, an entire size of the mechanical seal mechanism **332** can be reduced.

In this embodiment, since the seal liquid inlet **371** is opened upwardly in the diagonal direction, a flowing-in

sealing liquid is directly hit upon the sealing portion, cooling it more effectively. The fourteenth embodiment has the same structure as that of the tenth embodiment shown in FIG. **25** except for the aforementioned respects. To avoid repetitions in FIG. **29**, like reference numerals designate like structural elements explained in FIG. **25** showing the tenth embodiment.

The application of the mechanical seal mechanism according to the fourteenth embodiment shown in FIG. **29** is not limited to the artificial heart having a centrifugal pump mentioned above. It may be, of course, used in the artificial heart having an axial-flow pump mentioned above.

In both the fifth and sixth embodiments of FIGS. **19** and **20**, the driving shaft **230** mounts a pin **262** (illustrated only in FIG. **19**) which engages a recess in the follower ring **134**. Consequently, upon rotation of driving shaft **230**, the rotor boss **223** and associated parts including hollow ring **134** rotate in response to rotation of driving shaft **230**.

Additional advantages and modifications will readily occur to those skilled in the art. Therefore, the invention in its broader aspects is not limited to the specific details, and representative devices shown and described herein. Accordingly, various modifications may be made without departing from the spirit or scope of the general inventive concept as defined by the appended claims and their equivalents.

What is claimed is:

**1.** An artificial heart for embedding in a heart of a human body comprising:

- a casing including first and second inlet ports, first and second outlet ports, a first passage defined in the casing and in communication with said first inlet and outlet ports, and a second passage defined in the casing and in communication with said second inlet and outlet ports;
- a first pump mechanism provided in said first passage;
- a driving mechanism for driving said first pump mechanism so that blood is sucked at the first inlet port, flows through the first passage and is discharged from the first outlet port, said driving mechanism including a driving shaft and a motor for rotating the driving shaft;
- a sealing mechanism provided between the first and second passages to seal the first passage against the second passage so that blood flowing through the first passage is prevented from entering in the second passage, the sealing mechanism being exposed to the first passage, said sealing mechanism including a movable seal member attached to the driving shaft and having a first seal surface, and a stationary seal member having a second seal surface, and further including means for urging the driving shaft to make the first seal surface contact the second seal surface to define a boundary therebetween;
- a third passage in communication with said second inlet and outlet ports; and
- a second pump mechanism for circulating a sealing liquid between the second and third passages to make the sealing liquid contact the sealing mechanism.

**2.** The artificial heart according to claim **1** wherein said casing includes a pump section provided on one side thereof and housing the first pump mechanism therein, and a driving section provided on the other side of the casing and housing the driving mechanism, and wherein said first inlet and outlet ports are arranged on the pump section, and said second inlet and outlet ports are arranged on the driving section.

**3.** The artificial heart according to claim **2** wherein said driving shaft extends to the pump section from the driving

section and wherein said first pump mechanism includes an impeller attached to the driving shaft.

4. The artificial heart according to claim 1 wherein said movable seal member includes a seal ring coaxially attached to the driving shaft, the seal ring having one surface provided with a central recess therein and an annular peripheral area defining said first seal surface, and said stationary seal member includes a mating ring having an annular surface defining said second seal surface.

5. The artificial heart according to claim 4, wherein each of the first and second seal surfaces is a flat surface.

6. The artificial heart according to claim 1 wherein said first pump mechanism includes a centrifugal pump.

7. The artificial heart according to claim 1 which comprises a flexible tube define said third passage therein, and

wherein said second pump mechanism includes a pump provided on the flexible tube.

8. The artificial heart according to claim 7 which comprises a container for storing the seal liquid therein, provided on the flexible tube.

9. The artificial heart according to claim 8 which comprises a filter provided on the flexible tube, for removing foreign matter in the sealing liquid circulating between second and third passages.

10. The artificial heart according to claim 9 wherein said filter is mounted on the container.

11. The artificial heart according to claim 1 which includes a filter for removing foreign matter in the sealing liquid circulating between second and third passages.

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